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ABSTRACT

The text is a compilation of background information which should be useful to teachers wishing to obtain some technical information on solar technology. Twenty sections are included which deal with topics ranging from discussion of the sun's composition to the legal implications of using solar energy. The text is intended to provide useful information to teachers at all levels of secondary education. Many advanced science teachers with competency in algebra may find the text useful. (Author/RE)

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Text

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SOLAR ENERGY PROJECT

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SOLAR ENERGY TEXT

THE TEXT IS A COMPILATION OF BACKGROUND INFORMATION WHICH SHOULD BE USEFUL TO TEACHERS WHO WISH TO OBTAIN SOME TECHNICAL INFORMATION IN THE SOLAR AREA. THERE ARE TWENTY SECTIONS DEALING WITH TOPICS RANGING FROM THE SUN'S COMPOSITION TO THE LEGAL IMPLICATIONS OF USING SOLAR ENERGY. THE TEXT IS WRITTEN SO THAT TEACHERS AT ALL GRADE LEVELS, 7-12, MAY GET SOME HELPFUL INFORMATION. ALTHOUGH THE PRIMARY AUDIENCE IS INTENDED TO BE TEACHERS, MANY ADVANCED SCIENCE STUDENTS WITH A COMPETENCY IN ALGEBRA MAY FIND THAT A VARIETY OF SECTIONS ARE USEFUL.

ACKNOWLEDGEMENTS

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TABLE OF CONTENTS

SECTION I

OUR ENERGY SOURCE - THE SUN

Our sun is just one of [illegible]ess number of stars found in the universe. As far as stars go, it [illegible]y very noteworthy. However, as far as life on this planet goes, it is [illegible]portant. It is certainly not the largest nor the smallest, the oldest nor [illegible]oungest, the hottest nor the coldest. Astronomers classify it as a "main sequence", spectral class "G" star. Stated simply, this means that our sun is an average run-of-the-mill star with a good many years of life still remaining. For about five billion years the sun has been providing the earth with nearly all of its energy; we can count on it to continue to do so for the next five billion years. It is the only star close enough to enable scientists to study it in rather fine detail.

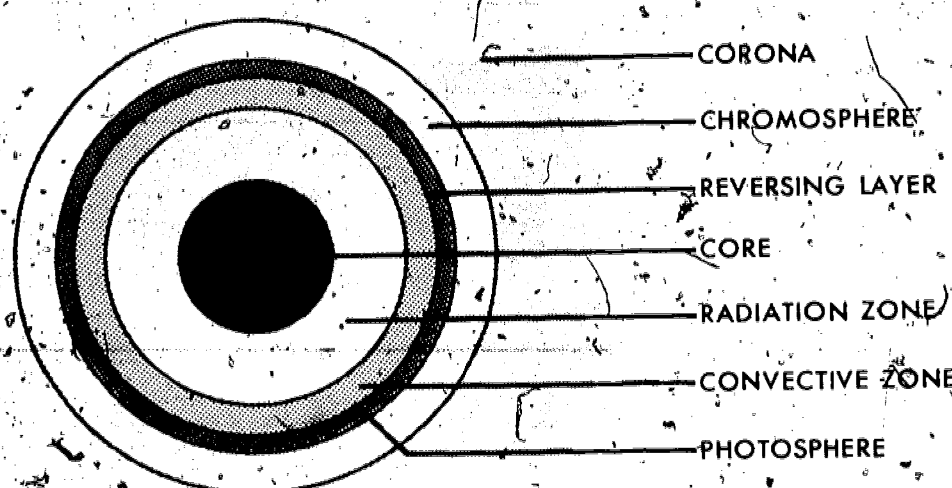
The earth revolves around the sun in an elliptical orbit at a distance of approximately 93 million miles. At this distance, it takes light and other radiant energy from the sun about eight and one-half minutes to reach earth. Because of the slight eccentricity of the earth's orbit, we are somewhat closer to the sun during winter months than in summer. The sun and the moon, when viewed in the sky, appear to be approximately the same size; roughly, they appear to have an angular diameter of about $1/2^{o}$. However, the moon is only 240,000 miles away. When one realizes that the diameter of the sun is about 864,000 miles or over three times the distance from the earth to the moon, one begins to appreciate how large the sun really is. The volume of the sun is about 1,300,000 times that of the earth. The mass of the sun can be determined by measuring its gravitational effect on the earth and is found to be about 2×10^{30} kilograms or about 330,000 times that of the earth. Knowing the mass and the volume, one can calculate the sun's average density; this turns out to be 1.4 grams/cubic centimeter. On earth this would normally suggest either a material in the solid or liquid state. However, under extreme pressure and temperature, gases also have densities of this order. Pressure in the interior of the sun probably reaches 1×10^{12} pounds/inch^2, while you will recall that normal atmospheric pressure on the earth is about 14.7 pounds/inch^2.

The sun, like the earth, rotates on its axis from west to east. The sun's equator is inclined about 7° to the plane of the ecliptic (the ecliptic is the apparent path of the sun as it moves through the sky among the other stars). Unlike the earth its period of rotation varies with latitude; the period of rotation on its equator (0° latitude) is slightly less than 25 earth days. The period increases to about 33 days in its polar regions. These differences are possible because of the gaseous nature of the sun. Such periods can be determined by studying the doppler shift with a spectroscope or, for that matter, by merely observing the movement of sunspots across the face of the sun.

The sun is made up of various layers; the boundaries are rather indistinct and represent areas where certain dynamic processes give way to others. The part of the sun that we see is called the photosphere. It is a relatively thin layer about 200 or 300 miles thick. Study of this "surface" using proper filters reveals bright granular areas 300-600 miles in diameter surrounded by a darker background. These are not permanent features and last only for a few minutes. The patterns are probably caused by hot gases moving upward at a velocity of about 1 mile/second while surrounded by cooler, darker looking gases. The temperature of the photosphere is about 6000°K ($^{\circ}$K stands for degrees Kelvin. A Kelvin degree is the same size as a Celsius degree; however, the Kelvin or absolute temperature scale starts out at absolute zero, or -273^{o}C. (^{o}C = ^{o}K - 273^{o})). The density of the photosphere is perhaps about 1/1000 that of the earth's atmosphere at sea level.

Directly beneath the photosphere is the convective zone. This layer, about 50,000 miles thick, is racked with violent convective currents transferring energy up from the radiation zone. The radiation zone extends downward towards the core. Here energy is transferred upward chiefly by waves of radiation traveling at the speed of light (186,000 miles/second). By the time we reach the core, we find temperatures in the neighborhood of 16,000,000^{o}K (25,000,000^{o}F) and pressures one hundred billion times larger than atmospheric pressure on earth. It is here that continuous thermonuclear reactions occur. Before discussing these reactions, the source of the sun's energy, let us examine the outer layers of the sun.

STRUCTURE OF SUN



(Diagram not drawn to scale.)

Just above the photosphere is a cooler layer (about 5000°K) called the reversing layer. It is called this because it absorbs and then reradiates some of the energy passing through it in all directions. Such absorption results in the characteristic dark-line spectra (Fraunhofer lines) seen against the continuous spectrum produced by the photosphere. These are observed and photographed in spectrographic studies of the sun. Helium was first discovered on the sun in this way. Absorption spectra show that approximately 70 elements exist on the sun. The five most abundant elements are hydrogen (90%), helium (10%), oxygen (.06%), nitrogen (.03%), and carbon (.02%).

Moving still outward we find the region known as the chromosphere. This extends about 6000 miles or more above the photosphere. When special equipment is used to block out the bright background light from the photosphere, this reddish-appearing region can be seen. The color is due to the most abundant gas, hydrogen, found in the region. Hydrogen gas has a strong red spectral line. Most of the gas in the upper part of the chromosphere is ionized. (Ions are atoms which have lost or gained electrons and therefore carry an electric charge.). The temperature in the upper reaches of the chromosphere is high. (100,000°K or higher). However, the pressure is very low.

Finally we reach the corona. This pale white halo extends one or two sun diameters beyond the sun and can be readily seen during a total solar eclipse. It can also be observed at other times using a coronagraph. The corona appears to be made up of charged particles (protons especially) streaming away from the sun at velocities of several thousand miles per second. Here the temperature is very high, 1 million degress °K. However, the pressure is exceedingly low creating an almost perfect vacuum. Consequently, this temperature is a kinetic temperature based on the average kinetic energy of the moving particles. The equilibrium radiation temperature of an object placed in the corona would be much lower; in fact, it would be extremely cold were it not for energy received by radiation from the photosphere. The so-called "solar wind" is believed to be merely an extension of the corona reaching out beyond earth and the other planets of our solar system.

A number of dynamic transitory phenomena are observed occurring at various levels in the solar atmosphere. Sunspots, which appear as slightly darker areas on the sun's surface, may develop especially in a narrow region about 40° north or south of the equator. These appear to follow an 11 year cycle in which solar activity rises and then falls. Smaller sunspots are about the size of the earth; larger ones could hold thousands of earths.

Prominences, condensed streams of hot luminous gases, can be seen at times extending thousands of miles into the corona. When seen against the background of the sun they appear as darker filaments, often taking on an arch shape as they loop back to the surface. These relatively long-lived phenomena seem to originate near sunspot groups. Flares are bright, short-lived phenomena reaching their greatest intensity in a matter of minutes and lasting, perhaps, as long as an hour. They usually originate from plage, bright areas bordering sunspots.

One flare may release as much energy as one billion hydrogen bombs. If it were not for our earth's protective magnetic field and atmosphere, a single solar flare could wipe out all life on earth with its x-ray and ultraviolet rays. On the surface of the sun small bright spots have been identified in x-ray studies. These are scattered over the surface of the sun and are not restricted to certain regions as sun spots are. They appear to be associated with local areas of intense energy emission. Even within the solar corona, great explosions have been recently observed; these have been called "coronal transients". Hugh quantities of materials, hundreds of thousands of tons, are hurled outward into space at enormous velocities.

It can be seen that our nearest star is in a constant state of transformation. It is fortunate that the earth is far enough from this violent rotating sphere of gases to enjoy a continual stream of radiation at intensities that are both safe and essential to life.

SECTION II

ENERGY PRODUCTION ON THE SUN

Occasionally one hears the sun described as "a hot ball of burning gases." This, of course, is a very poor description since the gases on the sun are not burning in the usual sense of the word. Burning refers to a chemical process where a material combines with an oxidizing agent, often oxygen, in an exothermic reaction giving off heat and light energy. The process occurring on the sun is a nuclear reaction and quite different from the chemical reactions by which most of our heat energy on earth is now derived (burning oil, gas, coal, etc.). Chemical reactions involve rearrangement of the electrons of the atoms; nuclear reactions involve changes within the nucleus itself. The energy release associated with nuclear reactions is enormous compared to that associated with chemical reactions involving the same quantity of matter.

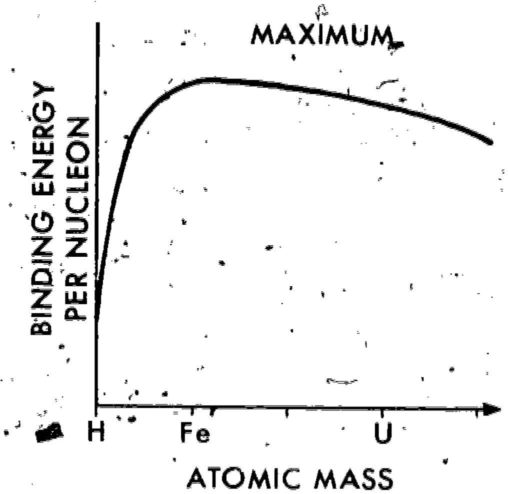
There are several kinds of nuclear reactions. For example, there are a number of naturally occurring radioactive substances such as uranium, thorium, etc.; usually these are relatively heavy elements. Spontaneously, some of the nuclei in atoms of these materials undergo a nuclear change in which α particles (helium nuclei) or β particles (high-speed electrons) are given off. Such emissions change the nucleus into a new element with a lower atomic number and weight or into a new element with the same atomic weight but with a higher atomic number. Through a series of such changes, these atoms ultimately become stable, nonradioactive substances having smaller atomic weights and numbers.

A very few kinds of nuclei undergo a different sort of change. A nucleus of the isotope uranium 235 (235 is the mass number or atomic weight), when bombarded with low energy neutrons, may capture one and become unstable.

This causes it to split into two smaller nuclei such as barium and krypton and at the same time give off several additional neutrons plus a large amount of energy. This is the basis of the atomic bomb as well as the controlled, chain reaction in nuclear power reactors. This process is known as fission.

A third kind of nuclear reaction known as nuclear fusion involves essentially the opposite sort of process. It involves the combining of several small nuclei into one larger nucleus with the subsequent release of huge amounts of energy. This process occurs on the sun. In order for such a reaction to occur, temperatures must be extremely high, on the order of many millions of degrees. A fusion reaction is therefore often called a thermonuclear reaction. So far, man has not been able to produce a useful, controlled, fusion reaction; he has, however, produced the fusion or hydrogen bomb, a bomb of enormous destructive capability.

In order to understand why these nuclear reactions are possible, one needs to understand the relationship between atomic mass and binding energy. It can be shown that the mass of a nucleus is somewhat smaller than the mass of the individual particles of which it is composed; this difference is known as the mass defect. Years ago, Einstein proposed that mass and energy are equivalent and are related by the relationship $E = mc^2$, where E is energy measured in appropriate units, m is mass, and c is a constant, the speed of light. The difference in mass between the sum of the masses of individual particles that make up a nucleus and the actual mass of the nucleus itself then represents a certain amount of energy. This is the same amount of energy that would have to be expended to break up a nucleus into individual particles; this is known as the binding energy.



It can be seen in the diagram above that atoms of intermediate size such as iron (Fe) are the most stable since they have the greatest binding energy per nucleon (nuclear particle). Increased stability can therefore be achieved by more massive atoms giving off α and β particles and ultimately becoming smaller stable atoms. This can occur by certain larger, unstable atoms undergoing fission and breaking into smaller, intermediate-sized atoms, or by several smaller atoms combining to form a larger, more stable nucleus. In each case matter is converted to energy according to Einstein's equation $E = mc^2$. Fusion reactions can be seen as offering the largest release of energy per nuclear particle.

Scientists believe that the sun and its planets formed out of a large, contracting cloud of gas and dust. As the sun grew larger and larger, its gravitational force increased. It continued to attract more and more matter and grew even larger. Finally, pressure and temperature increased in its interior until they reached that necessary to sustain a fusion reaction. It is estimated that the temperature of the core of the sun reaches 25,000,000^{o}F, with pressure on the order of about one trillion pounds per square inch. It is almost impossible to conceive how hot this really is; it has been said that a tiny piece of this material the size of the head of a pin one hundred miles away would be hot enough to burn one to a crisp. Physicists have theorized that there are two possible fusion reactions that can account for the energy produced by the stars. One is known as the proton - proton reaction; the other is the carbon - nitrogen cycle. The latter one requires higher temperatures than exist on the sun and is therefore an important process for stars larger than the sun. Both reactions have the same end result: four protons (hydrogen nuclei) are converted into one helium nucleus. The series of reactions in the proton - proton reaction are given as follows in equation form:

$${}_1H^1 + {}_1H^1 \longrightarrow {}_1H^2 + {}_1e^0 + \text{neutrino}$$

$${}_1e^0 + {}_{-1}e^0 \longrightarrow \text{gamma ray}$$

$${}_1H^2 + {}_1H^1 \longrightarrow {}_2He^3 + \text{gamma ray}$$

$${}_2He^3 + {}_2He^3 \longrightarrow {}_2He^4 + {}_1H^1 + {}_1H^1 + \text{gamma ray}$$

${}_1H^1$ = hydrogen nucleus

${}_1H^2$ = deuterium - heavier isotope of hydrogen

${}_2He^3$ = an isotope of helium

${}_2He^4$ = common helium

${}_1e^0$ = positron

${}_{-1}e^0$ = electron

In this reaction four hydrogen nuclei are converted into one helium nucleus. Four hydrogen atoms have an atomic mass of 4 x 1.008 atomic mass units (a.m.u.'s) while the resulting helium atom has an atomic mass of 4.003 a.m.u.'s. No electrons are involved in this reaction and therefore their mass can be ignored. This leaves a mass difference of 0.029 atomic mass units so that roughly 0.7% of the matter has been converted to energy according to the relationship $E = mc^2$. Each second over 4 million tons of hydrogen are converted to helium; one can realize, then, that an enormous amount of energy is continually produced by the sun. It amounts to a power output of roughly 6×10^{23} hp. It might seem that at this conversion rate the sun would soon run out of hydrogen. This is not the case; the sun is so massive that there would still be plenty of hydrogen left after 150 billion years. Other changes, however, should limit the remaining life of the sun to about 5 billion years. Most of this energy is produced deep within the core of the sun where the temperature and pressure are greatest. It is estimated that about one one-thousandth of the solar volume produces roughly 50% of the total sun's energy. Initially most of this energy is in the form of gamma radiation. Gamma radiation is very high-energy electromagnetic radiation of the same sort as x-rays, ultraviolet, visible light, infrared (heat), and radio waves. These differ as to energy content; the shorter the wavelength (or higher the frequency), the higher the energy content according to the relationship $E = hf$ where E is energy, h is a constant (Planck's), and f is frequency.

All electromagnetic radiation travels at the speed of light. One might assume, then, that the energy produced within the sun arrives at the surface almost instantaneously. After all, it takes the sun's energy only 8 1/2 minutes to reach the earth. However, this is not the case; it is estimated that it takes as long as 20,000 years for the energy to reach the surface of the sun. This is due to the numerous collisions which occur en route to the surface; the closely packed protons, electrons, and other particles within the sun bounce the gamma rays back and forth. In the process, the initial gamma radiation is converted to some of each of the kinds of electromagnetic radiation mentioned above. At the surface of the sun, we find a distribution of energy as follows: approximately 41% of the energy lies in the visible light region with wavelengths between 3800 Å and 7600 Å. (Å refers to an Angstrom unit; 1 Å = 10^{-10} meters). Another 50% of the energy has wavelengths larger than visible light and therefore lies in the infrared region; a very small percentage of this falls in the radio wave region. The rest, approximately 9%, has higher energy waves in the ultraviolet or even x-ray region. These of course are short, high-frequency waves.

As might be expected, the energy released per unit area of the sun's surface is tremendous. Each square foot of the sun's surface radiates energy at the rate of about 7,780 hp. Another way of looking at this is that each square centimeter of solar surface radiates about 100,000 calories per minute. A calorie is the amount of heat needed to raise the temperature of 1 gram of water one Celsius degree. Still another way of looking at the energy emitted is in terms of the brightness or luminosity of the sun. An ordinary 60-watt light bulb may have a total light output of about 70 candlepower; the sun has an output of 1,500,000 candlepower per square inch of surface. All of this energy is radiated outward in all directions. The earth is 93 million miles away and occupies a tiny spot in space. Only a small proportion of the sun's total radiant energy sweeps across this tiny target. At the very top of the earth's atmosphere approximately 1.94 calories per minute are received by each square centimeter of a surface aligned perpendicular to the sun's rays. While this may seem like a very tiny bit of energy compared to that available at the sun's surface, it still amounts to about one-half million hp/square mile. If this energy were able to penetrate the earth's atmosphere intact and reach the earth, it would amount to approximately 210 trillion hp; more than 500,000 times the capacity of all electric generating plants in the United States.

This average value of 1.94 calories/square centimeter/minute or 1.94 Langleys/minute is known as the <u>solar constant</u>. Actually it varies slightly as the earth - sun distance changes during the year. There is some evidence that this "constant" may vary 2% or 3% with changes in solar activity. This value can also be expressed as 1360 watts/square meter. What happens to this energy as it travels down through the earth's atmosphere and how much ultimately arrives at the earth's surface will be discussed in one of the following sections.

THE EARTH - A SOLAR COLLECTOR SYSTEM IN SPACE

Ideally, a solar collector system should convert radiant energy received from the sun into usable energy forms. It should do this with high efficiency and minimum loss. Since the sun does not provide a constant source of energy at all times and places on earth, the system must have energy storage capability and some mechanism for energy transport when needed. Specific systems will be discussed later; in general, though, they consist of 4 or 5 essential components:

<u>Glazing</u>: The purpose of the glazing, or cover for the collector is to admit as much of the incoming radiation as possible and at the same time prevent the convective heat loss from within the collector. In other words, the glazing must be transparent to incoming radiation and opaque to outgoing radiation. Here is where knowledge of radiation laws will help. The wavelengths of the maximum amount of radiation emitted by an object varies inversely with its absolute temperature: (Wein's Law)

$$\lambda \text{ max} = \frac{{}^{\circ}K}{T^{\circ}K}$$

The temperature of the sun's surface is roughly 5800°K. Substituting the equation:

$$\lambda \text{ max} = \frac{.29 \text{ cm}^{\circ}K}{5800^{\circ}K} = 5 \times 10^{-5} \text{ cm or } .5\mu$$

(often electromagnetic wavelengths is expressed in units of microns, μ; [$1\mu = 10^{-4}$cm]). This places the maximum radiation emitted from the sun's surface in the ultraviolet region.

On the other hand the temperature of the surface of the receiver is much lower. For example, to start with, it might be about 15°C

(64°F or 288°K). This temperature happens to be the approximate mean temperature of the earth.

$$\lambda\text{max} = \frac{.29\ \text{cm°K}}{288°\text{K}} = 10^{-3}\text{cm or } 10\mu$$

A wave 10μ long happens to be in the middle of the infrared band. A good glazing materials would be one that would admit ultraviolet and visible light but would be opaque to infrared. Glass, fiberglass, and certain other plastics admit visible light and, in some cases, ultraviolet but are opaque to infrared.

Collection Plate: The collection plate is the part of the system that intercepts the sun's rays. Ideally it's surface should be oriented at right angles to the rays so that it receives maximum energy per unit area. It should absorb as much of the energy received as possible with minimum reflection. In general, this means it will have a dark color and relatively large surface area per unit volume. It should have good heat conductivity so that it can readily transfer energy to the trnasparent medium. If possible, it should have a selective surface; one which absorbs energy of incoming radiation readily but reradiates little of the longer wavelength infrared. Man-made solar collectors use copper, aluminum, steel, and some plastics as collector plates, with black paint or selective surfaces of other materials.

Energy Transport Mechanism: Since energy must be moved over considerable distances, energy transport by convective means, either natural or forced, is generally used. This means that fluid such as air, water, or mixtures of water-glycol or other special liquids must be used. These should have high heat capacity and low viscosity; they should also be cheap, noncorrosive, stable and not freeze under design conditions. Fans or pumps may be needed to create pressure differentials in order to produce sufficient flow rates; in some cases, temperature differences between storage unit and collector may be sufficient to provide adequate convective flow. Copper or aluminum tubing is often used to transport liquids while ducts are used for air.

Energy Storage Medium: This may be a reservoir of the same material used to transport energy or it may be a separate substance coupled with the energy transport system through a heat exchanger. It should have high heat capacity (high specific heat) and it should be stable at design temperature. Since large quantities may be required, it must be relatively inexpensive. Substances such as water, pebbles, sand, concrete blocks, etc. have been used. In addition, use is sometimes made of substances that undergo phase changes at suitable design temperatures; the rather large amount of energy released or absorbed in such changes minimizes the amount of materials needed. Substances such as eutectic salts, salt hydrates, paraffin, etc. are being tested for this purpose.

Container: In order to minimize conduction, radiation, and convection losses, the various components of the system must be contained and provided with sufficient insulation. The container holding the collection plate may be metal, fiberglass, or even wood. It should be resistant to ultraviolet degradation and temperatures of several hundred degrees (400^{o}F). Insulation such as fiberglass, polyurethane foam, etc. can be used to minimize heat loss.

In operation, the solar collector is positioned so that incoming solar radiation reaches the collector plate. The glazing permits most of the ultraviolet and visible light to pass through it; a small amount of energy is absorbed by the glazing and an additional amount is reflected back. The amount reflected depends to some extent on the orientation of the collector; less light is absorbed and reflected when the glazing is perpendicular to the sun's rays. Transmitted radiation strikes the collector plate. Again a small amount of energy is reflected; most, however, is absorbed. The atoms of the collector plate gain kinetic energy and the temperature rises. Like any other body, the collector plate radiates energy. However, its temperature is low [illegible] only infrared radiation is given off. The glazing traps the infrared radiation and the air temperature above the collector plate continues to rise. As the temperature inside the container increases, conduction heat losses increase because of the increased temperature difference between inside and out. Also, the radiation losses increase due to their dependence on the fourth power of the temperature. Eventually equilibrium is established; the temperature inside the collector reaches some maximum value. At this point, the heat losses of all kinds just balance the heat input.

Normally, as soon as the temperature of the collector is slightly above the temperature of the energy storage medium, the energy transport system becomes operable. Therefore, instead of reaching some higher static temperature the collector remains much cooler as energy is removed continuously. As the sun's energy diminishes, a point is reached where the collector temperature drops below the temperature of the energy storage medium. At this point the transport system no longer circulates the medium through the collector. If heat is needed, it is obtained directly from the energy storage system. Eventually the temperature of the storage medium drops below the collector temperature and the cycle is ready to be repeated.

Let us now look at the earth in terms of a solar collector system in space. The cross sectional area of the earth is that area lying perpendicular to the sun's rays and therefore equal to the area of the collector plate. Just outside the earth's atmosphere energy arrives at the rate of 1.94 cal/cm^2/min or 1360 watt/meter. This energy, if it were to reach the earth's surface undiminished, would be spread out over the total surface area of the earth's sphere as a result of the daily rotation of the earth. The area of a sphere is $4\pi r^2$, therefore, the average energy available on each square centimeter of the earth's surface is 1/4 × 1.94 cal/min or .485 cal/min assuming no depletion of energy as it passes through the atmosphere. This, however, is not the case. As we will see in the next section, reflection and reradiation amount to roughly 50% of the incoming radiation. This further reduces the available energy rate to $\frac{.485}{2}$ cal/cm^2/min or approximately .25 cal/cm^2/min (or 170 watts/$meter^2$). Even so, this amount of energy exceeds by many thousands of times the world's total energy use.

The earth's upper atmosphere serves admirably as the glazing. It is relatively transparent to most of the incoming radiation except, luckily, the high energy ultraviolet which, if not stopped, would destroy all life on our planet. Furthermore, it is opaque to much of the lower energy radiation emitted by the earth. The lower atmosphere serves both as the energy transport system and an energy storage medium. Since the earth is spherical, parts of the earth's surface are aligned at right angles to the sun's rays while other parts are almost parallel. It is obvious that in a course of a year the equatorial regions will receive much more energy than the polar region because of their orientation to the sun's rays. Furthermore, even during the course of a day, direct radiant energy received at any location will vary from zero at night to some maximum value near noon. The earth, therefore, needs an energy storage and transport system. Convective currents of air remove excess heat energy from equatorial regions and move it to the polar region where it is needed. Evaporative processes also tend to store and transport large amounts of energy in the lower atmosphere in the form of water vapor. In addition to acting as the collector, the earth's surface also acts as an energy storage device. In particular, large bodies of water with high specific heat and high transmission of radiant energy (compared to land) tend to act as good heat reservoirs. Thus oceans aid the atmosphere in energy transport. Details of each of these major processes are covered in following sections.

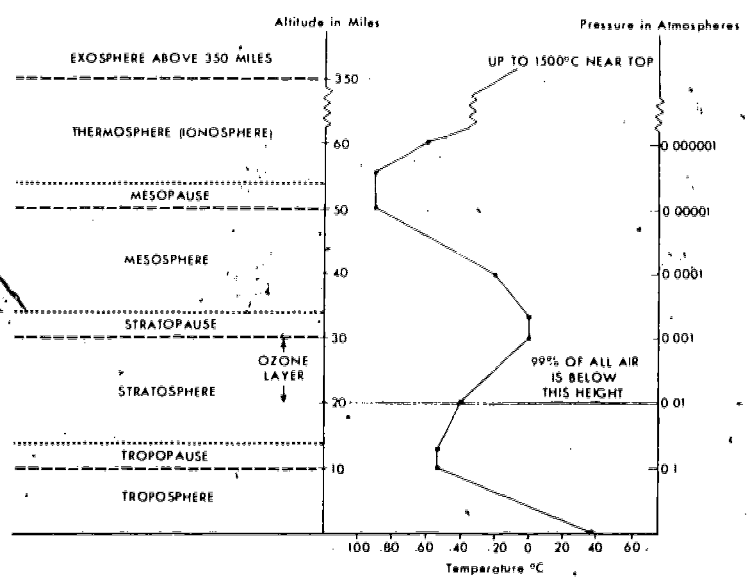
SECTION IV

THE EARTH'S ATMOSPHERE - THE GLAZING

The earth's atmosphere is a mixture of various gases: Nitrogen, 78%, Oxygen, 21%, Argon, 0.9%, Carbon Dioxide, 0.03% and traces of others, including neon, helium, methane, sulfur dioxide, nitrous oxide, and ozone. These percentages are fairly constant to elevations of 50 to 100 miles. At 500 to 1000 miles only the lightest gases like hydrogen and helium are found in abundance. Water vapor, another gas found in the lower portion of the atmosphere, varies in abundance up to about 4% by volume.

In order to understand the dynamic processes which occur in the atmosphere, it is necessary to know something about its vertical structure. Some important data are summarized in the diagram below:

STRUCTURE OF ATMOSPHERE



Troposphere: The average height is about 40,000 feet (12,200 meters). This is the region where nearly all the clouds, moisture content, and "weather" are found. It is a region of convection and vertical mixing. The temperature decreases with altitude until the tropopause is reached; this decrease is roughly 3.6°F per 1000 feet (2.0°C per 305 meters) altitude. About 75% of all atmospheric mass in our latitude is found here; the value is even higher for the tropics.

Tropopause: This marks a place where the temperature begins to increase with altitude, forming an inversion.

Stratosphere: This zone is roughly 20 miles thick, from 8 miles to 30 miles in height. The temperature increases with altitude from about -55°C to 0°C or even higher. It differs from the troposphere mainly in its low, stable, water vapor content, lack of clouds, and increased ozone content near its top. Ozone (O_3) is produced by the bombardment of oxygen molecules (O_2) by intense ultraviolet radiation. Here atmospheric density is about 1/1000 of that near the surface. The fewer molecules per unit volume of gas no longer effectively shield against the ultraviolet radiation.

Stratopause: Above this boundary the temperature starts to drop again.

Mesosphere: In the mesosphere the pressure continues to drop; here molecules of oxygen (O_2) and nitrogen (N_2) still persist. The distance between molecules is becoming greater and greater. Near the top at a height of about 50 miles, the temperature drops to nearly -100°C. Here we find ionization beginning to occur. Ions are atoms or molecules with an electrical charge, that is, they are not electrically neutral. They are produced here by the bombardment of gaseous molecules by high energy radiation from the sun.

<u>Mesopause</u>: Here again there is a reversal in the temperature trend at this boundary.

<u>Thermosphere or Ionosphere</u>: This region extends from about 50 miles to 350 miles. The temperature rapidly climbs to over 1500°C near the top of the thermosphere. This region is characterized by considerable electrical activity resulting from bombardment of molecules of gas by high energy solar radiation. The high temperature is caused by the presence of atomic oxygen (O), which absorbs certain wavelengths of energy from the sun. Particles are so far apart that they travel hundreds of feet before colliding. The temperature is a kinetic temperature rather than the usual equilibrium radiation temperature. Thus an object placed in the atmosphere here would remain much colder than expected. Actually, the ionosphere is divided into a number of layers of special interest to communication engineers because of their effect on the transmission or reflection of certain radio frequencies. However, for our purpose, it is sufficient to know that most of the gamma radiation, x-rays, and some of the ultraviolet radiation is absorbed by the various layers of this region.

<u>Exosphere</u>: Finally we come to the region which extends to outer space. Here are found the Van Allen radiation belts. The earth's magnetic field seems to be the dominant factor in controlling the motions of the particles found in this region.

Now that we have examined the vertical structure of the earth's atmosphere, we are ready to examine more closely what effect this has on the energy received from the sun as it enters the atmosphere and continues on its journey to the earth's surface below. Before reaching the atmosphere, there has been little loss in the amount of radiation emitted from the sun. But now the quanta begin to interact with the particles making up the atmosphere and losses in energy can be expected. The losses that occur cause the "depletion of the solar beam". Various wavelengths are acted on selectively. High in the atmosphere, depletion begins as ultraviolet radiation when wavelengths shorter than $2400\mathring{A}$ or $.24\mu$ collide with widely spaced oxygen molecules, (O_2), breaking them into atomic oxygen (O). Because of the low density of the gases, there is little tendency for atomic oxygen to recombine. These collisions remove most of the very high energy radiation, including gamma rays and x-rays. At an altitude of about 30 miles, sufficient O_2 molecules exist to permit their conversion into O_3 according to the reaction: $3O_2 \xrightarrow{u.v.} 2O_3$

Although ozone exists in the atmosphere in amounts of only .2 ppm (.2 parts per million), it plays a major role in screening out ultraviolet radiation. Nearly all ultraviolet radiation below $.3\mu$ is absorbed by the O_3, roughly 2 to 3% of the original radiation entering the atmosphere. This energy absorption causes the temperature rise mentioned earlier. Only 1 to 3% of the total energy received on the earth's surface is ultraviolet.

As the solar beam continues, scattering of the shorter wavelengths (blue) of visible light occurs. As a result, the sky appears blue and the sun yellow or orange. The bluish light which would have reached an observer directly from the sun is scattered in all directions by interactions with molecules.

About 6% of the original radiation is scattered back out to space by the upper troposphere. Most of the visible light arriving from the sun does manage to penetrate to the surface and accounts for between 45 and 50 percent of the total energy received there. Two gases, carbon dioxide and water vapor, which make up a small percentage of the gases of the atmosphere, have a large effect on the absorption of infrared radiation. Water vapor, in particular, plays an important role in incoming infrared radiation absorption.

Clouds, of course, complicate the picture. High cirrostratus type clouds might reflect as little as 20% of the incoming energy. Heavy clouds of the altostratus type might reflect over 70% of the energy striking them. Averaged over the entire earth's surface, losses due to reflected radiation from clouds amounts to about 19%. In addition to the energy reflected, additional energy is absorbed by the water particles making up the cloud, perhaps another 5 or 6%. Additional losses in the incoming solar beam result from absorption of energy by various pollutants, dust particles, etc. Altogether, absorption losses from all sources reduce the incoming radiation by roughly 25%. Finally, reflection by the earth's surface itself removes another 3% of energy arriving from the sun. This leaves roughly 47% of the energy of the original solar beam available for absorption by the earth. Averaged over the surface of the earth this amounts to $\frac{1.94}{4} \times .47 = .23$ cal/cm^2/min or $\frac{1360}{4} \times .47 = 160^{W}/m^2$.

It should be noted that all of these percentages are estimates; in particular it has been very difficult to measure the amount of radiation reflected by the atmosphere. As a result, do not be surprised if you find different values stated elsewhere; often you will find the lower value of $135^{W}/m^2$ given as the amount of radiation actually absorbed by the earth. This assumes a somewhat greater "albedo", about 30% for the earth's atmosphere. "Albedo" is merely the ratio of the radiation reflected to the radiation received; it tells you the percentage of reflection.

So far we have examined the atmosphere as a glazing only for incoming radiation. One must also see how well it functions in retaining the energy received by the collector. As previously mentioned, the average earth temperature is about 15°C; this results in reradiation wavelengths in the infrared region with the maximum peak occuring about about 10μ. One must remember that any spot on the earth receives energy for only about 1/2 day whereas it reradiates continuously, 24 hours a day. The radiation from the earth's surface extends between about 4μ and 70μ; incoming radiation is all less than 4μ. Water vapor absorbs strongly between about 5μ and 7μ and again beyond about 12μ. CO_2 absorbs between 4μ and 5μ and, after a gap, beyond 14μ. O_3 absorbs a narrow band at 9.6μ. One can see then that two gases, H_2O and CO_2, effectively prevent the escape of most infrared radiation beyond about 4μ except for a band or "window" between 8μ an 11μ. Furthermore, those gases exist in greatest abundance in the very lowest layers of the atmosphere, thus keeping this energy close to the earth's surface.

We have now examined the earth's atmosphere in terms of its effects on incoming and outgoing radiation. It would appear to fulfill the requirements of a suitable glazing material for the solar collector called Earth.

SECTION V

HEAT TRANSFER - A MICRO COURSE

Before we examine what happens to the sun's energy as it continues on its path through the earth's atmosphere, it will be well to review heat transfer in general terms. In our discussion of the sun we mentioned the three ways in which heat energy can be transferred: radiation, convection, and conduction. Let us look a little more closely at each.

Heat is energy in transit between two substances at different temperatures; the flow is always from the higher to the lower temperature. Temperature, in itself, is not heat energy. Temperature is a measure of the average kinetic energy (energy of motion) of the particles making up a substance. The higher the temperature of a substance the greater the average kinetic energy of it's particles. For example, most substances expand as their temperature rises because the increased kinetic energy of each particle making up the substance is, on an average, higher and each particle effectively moves through more space. The amount of heat energy which can be transferred between two substances depends in part on the temperature of each substance, their specific heats, and their masses, $Q = MC\Delta T$. (Q stands for heat energy gained or lost; M the mass of the substance; C the specific heat of the substance, and ΔT, the temperature change of the material. This assumes no phase change has occurred.)

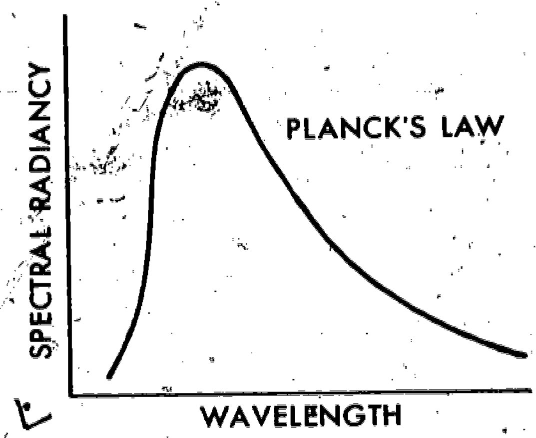
Heat can be transferred in one of several ways. Conduction is important in the case of solids, especially metals which are good conductors of heat energy. It involves transfer of kinetic energy from atom to atom or molecule to molecule. Heated molecules transfer some of their vibrational energy directly to their cooler neighbors. On a molecular level this results in large scale energy transfer. Tables have been prepared which give the thermal conductivities of various substances; the lower the conductance the better the insulating value. The amount of heat lost by conduction depends not only on the thermal conductivity of the substance but also upon the cross sectional area of the conductor, its thickness (or length), the temperature difference between the two surfaces, and the length of time considered.

Convection is especially important in the case of fluids (gases and liquids). It involves the transfer of heat energy by the actual movement of the heated fluid. The movement of the fluid is produced by forces arising out of differences in density which result from uneven heating effects. For example, the water in the bottom of a kettle next to the surface of the stove absorbs energy, expands slightly (causing its density to diminish) and is then bouyed upward by the surrounding, more dense, colder water. Convection currents are thereby set up that eventually distribute heat throughout the mass of water.

Since all of our energy from the sun comes to the earth by means of radiation, it is important to know something of the laws that govern radiation. Radiation involves the transfer of energy through space by electromagnetic waves. This is a very complex subject; it will suffice to say that these waves have electric, magnetic, and particle properties and they do not require a material medium in which to be propagated. These may be many meters long, in which case they are called radio waves, or exceedingly short, (10^{-12} meters) such as gamma rays. As indicated earlier, other electromagnetic radiation includes infrared radiation, visible light, ultraviolet light, and x-rays. All travel at the same spe through a vacuum: the speed of light, 186,000 miles/second or 3×10^{8} meters/ second. They arise as a result of accelerating changes. Some are produced as electrons change energy levels within the atom; others are related to changes within the nucleus itself. Radio waves can be produced by electrons oscillating in appropriate electric circuits. When these waves interact with matter they act as if their energy were contained in little bundles called quanta. This helps to explain why radio waves do not damage your body in the way x-rays do and why ultraviolet rays can give you a suntan but visible light cannot. Incidently, if you have forgotten the relationship between wavelength (λ), velocity (V), and frequency (f), it is found by the expression $V = f\lambda$, where V is a constant equaling the speed of light in the case of all electromagnetic radiation.

There are three laws of radiation that are useful in our work. Strictly speaking the laws apply to materials that are perfect absorbers and emitters of radiant energy ("black bodies"). However, they give very good approximations for the actual situation involved in solar radiation and energy absorbed or reradiated by the earth. The first of these laws is known as the Stefan-Boltzmann Law: The total energy emitted is directly proportional to the fourth power of the absolute (Kelvin) temperature, $E \propto T^4$ (Remember, $^{\circ}K = ^{\circ}C + 273^{\circ}$). The second of these laws is known as Wein's Law: The wavelength at which the radiation is most intense is inversely proportional to the absolute temperature of the source, $\lambda \max \propto 1/T^{\circ}K$ or written as an equation, $\lambda = K/T^{\circ}K$ where K is a constant, .29 $cm^{\circ}K$, λ is wavelength in centimeters, and T is temperature in $^{\circ}K$. One can see that the more the temperature increases, the shorter the wavelength of the maximum radiation will become. This explains why one would expect the radiation originating in the depth of the core of the sun (temperature = 16,000,000°K) to be very high energy gamma rays while that at the surface (temperature 5800°K) would be lower energy visible light or infrared.

The most general radiation law is Planck's law; it is rather complex and therefore instead of stating the mathematical form of the law a series of curves are plotted below to show the relationship between the amount of energy emitted and the wavelength for objects at different temperatures. One can see that the higher the temperature, the more the maximum energy (peak of curve) shifts toward the shorter wavelength. Also the total amount of energy at any particular wavelength increases with temperature. However, at any one temperature a wide spectrum of wavelengths are produced.



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SECTION VI

EARTH - ATMOSPHERE HEAT BALANCE

In the last section, the effect of the atmosphere on direct solar radiation was discussed. Scattering, reflection, and absorption reduce the incoming solar energy at the earth's surface to 47 percent of its original value. In order to maintain its overall mean temperature of 15°C, the earth must rid itself of this heat; equilibrium must be established with heat input equal to heat output. Applying the laws of radiation, one can calculate how much energy must be radiated from the earth's surface to maintain a mean temperature of 15°C, using the amount of direct radiant energy from the sun as the input. When this is done, a surprising result is found; the earth must radiate energy at its surface equal to 114 percent of the original solar beam (measured at the top of the earth's atmosphere).

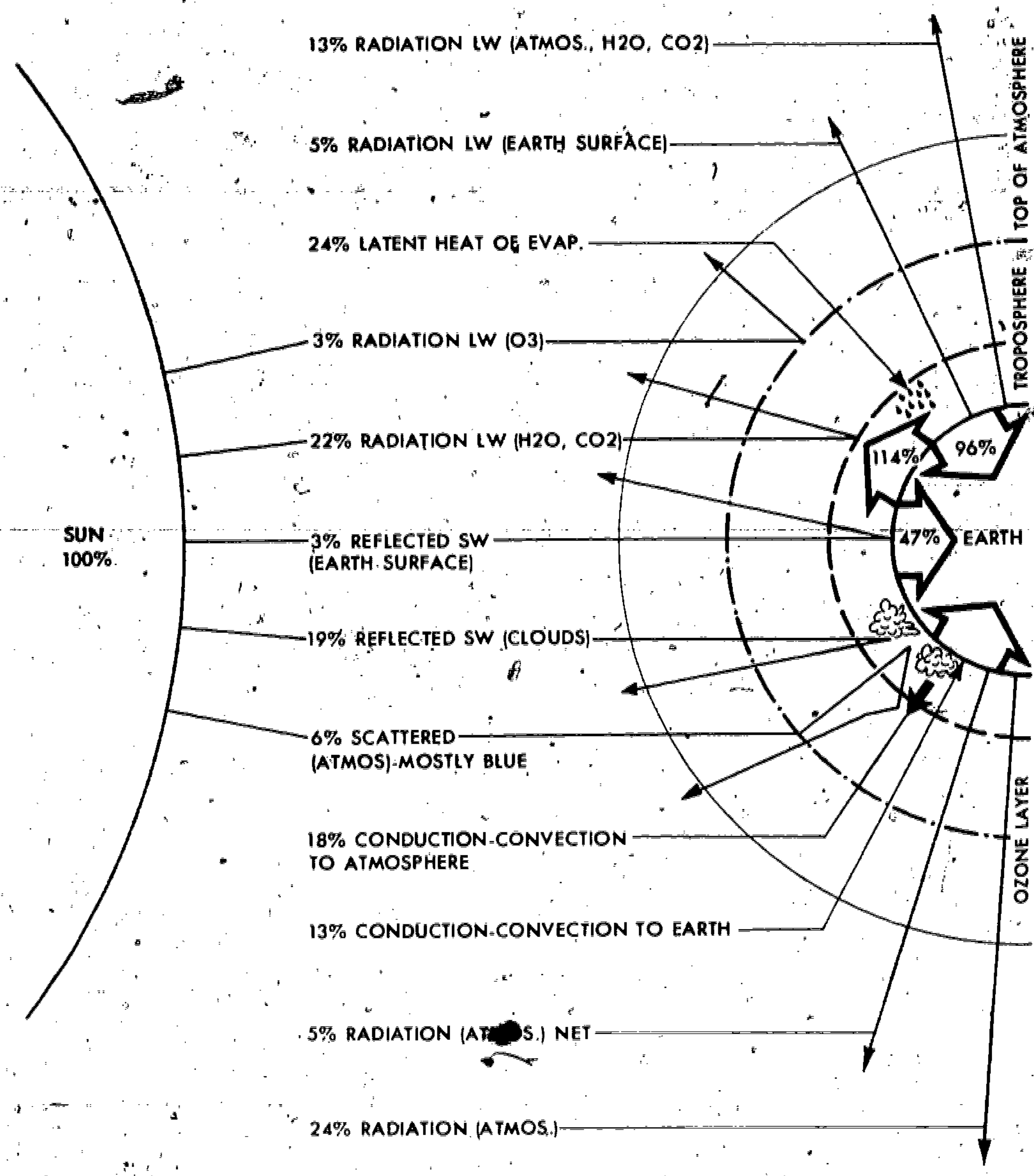
This suggests that we must look at the heat balance in the earth-atmosphere system. It is obvious from the law of conservation of energy that the total energy received by the system must be equal to the total energy given off by the system. The earth cannot give off more energy than it receives. However, the flow of energy into and out of the earth can be, and is, different than the radiant energy flow to and from the earth-atmosphere system. This means that processes other than direct radiation are operable. Apparently the earth is acting as a net absorber of radiant energy while the atmosphere is acting as a net radiator, with the whole system in balance with the energy input from the sun. If the earth is a net absorber of radiant energy, it must rid itself of any excess energy by other means. Let us consider some possibilities.

In addition to radiation, heat can be transferred by conduction and convection. So far we have been concerned with a kind of heat known as "sensible heat". It is the kind that your senses detect. It shows up as a change in temperature and it is the heat energy moved about by conduction, the heat released as fuel burns, or the energy stored as water is heated. The other kind of heat is "latent heat", or hidden heat. As it is stored, there is no change in temperature by the storing medium. For example, it takes over 500 calories to change 1 gram of water (liquid) to one gram of water vapor. (At the boiling point this value is 540 calories per gram and is known as the latent heat of vaporization). This is over five times the amount of heat needed to warm one gram of water from its freezing point to its boiling point. So it can be seen that the evaporation of water can store (and remove) large amounts of heat energy. Each gram of ice absorbs 80 calories of heat energy in melting. Other processes can also store latent heat.

The earth-atmosphere system as a whole receives a certain amount of energy from the sun. It is the system that must balance 100 percent energy outflow against 100 percent energy input. This balance is shown in the diagram below. At the edge of the atmosphere, the system receives 100 percent radiation input from the sun. Losses from the system include: 3 percent long wave radiation absorbed by the ozone layer; long wave radiation absorbed by water vapor, CO_2, and clouds (22 percent): short wave (visible light) reflection from clouds, (19 percent) and the earth's surface (3 percent), and scattering (6 percent). The rest, 47 percent, must be returned from the earth to the atmosphere and hence to space in order to give a net heat input-output flow of zero.

Consider now the surface of the earth. Here a balance must also exist. Net heat in must equal net heat out; otherwise, the temperature will change. However, the amount of energy transferred to and from the surface does not have

EARTH-ATMOSPHERE HEAT BALANCE



HEAT BALANCE: SYSTEM (EARTH-ATMOSPHERE)			HEAT BALANCE: EARTH	
ENERGY IN	ENERGY OUT (DIRECT)	ENERGY OUT (INDIRECT)	ENERGY IN	ENERGY OUT
SUN: 100%	22%	5%	47%	24%
	3%	13%	13%	114%
	3%	24%	96%	18%
	19%	5%	TOTAL:	
	6%		156%	156%
TOTAL: 100%	53%	47%		
NET ENERGY LOSS OR GAIN- 0			NET ENERGY LOSS OR GAIN-0	

to be the same value as that transferred between the sun and earth-atmosphere system. We have already said that the total energy radiated is 114 percent of the incoming radiation measured at the top of the earth's atmosphere. However, the amount of direct radiation from the sun amounts to only 47 percent. The diagram shows how this problem is solved. It is apparent that the earth receives a considerable amount of its energy from sources other than the original, direct solar beam.

Of the 114 percent long wave energy radiated from the earth's surface only about 5 percent escapes directly to space. This is the part of the infrared spectrum with wavelengths of 8-11μ. You will recall that there is a "window" in the water vapor absorption spectrum around 10μ. About 109 percent is trapped in the atmosphere by the water and CO_2 molecules. Of this about 96 percent is reradiated to the earth's surface; the rest, 13 percent, is radiated back to space. Thus, there is a net radiation loss of only 18 percent. We have already shown that the incoming radiation absorbed at the surface is 47 percent. How does the earth rid itself of the other 29 percent? Here is where the earth's storage and transport system must come to the rescue. Evaporation of water into the atmosphere accounts for the removal of another 24 percent of the absorbed heat energy, this time in the form of latent heat. In addition, conduction between the earth-atmosphere interface and convection removes another 5 percent as sensible heat. Actually, this is brought about by a 13 percent sensible heat input to the surface of the earth from the atmosphere which is offset by an 18 percent loss from the surface to the atmosphere. One should remember that short wave radiation from the sun heats the earth's surface and the atmosphere on only one hemisphere while radiation and conduction-convection losses are occurring over the whole sphere.

Checking out the heat balance, we find that a net radiation loss of 18 percent, a latent heat loss of 24 percent and a sensible conduction-convection loss of 5 percent just balance the 47 percent solar radiation input. Actually several smaller sources of energy have been ignored. These are so small they can be overlooked when calculations are made on a global basis. Locally, however, they may be significant. They include: The removal of energy through latent heat associated with photochemical processes, mainly photosynthesis ($-.13$ w/m^2), the addition of sensible geothermal heat ($+.06$ w/m^2), the addition of heat from fossil fuel burning ($+.02$ w/m^2), and heat added by metabolic processes ($+.0005$ w/m^2). Compared to the 135 w/m^2 solar input these are insignificant.

A similar sort of heat balance can be worked out for the atmosphere. Room does not permit showing it on the diagram. Here again heat input must equal heat output. Since the earth is a net absorber of radiant energy, the atmosphere must be a net radiator. The atmosphere acts as a good glazing material, trapping much of the earth's long wave radiation and then reradiating it back to the surface. Also much of the absorbed and scattered shorter wavelength radiation it receives finds its way to the earth's surface; such diffuse radiation accounts for a significant amount of the energy received by the earth.

The next section will deal with the atmosphere as a transport system. It has already been pointed out that far more solar energy arrives in the equatorial regions than at the poles. The only place that incoming radiation is equal to outgoing radiation is in the region near 36^{o} latitude. It becomes important, then, to understand the mechanism by which energy is distributed throughout the earth's surface by conduction-convection.

SECTION VII

THE EARTH'S ATMOSPHERE - THE ENERGY TRANSPORT SYSTEM

Over 2000 years ago, Archimedes discovered the principle that the buoyant force on a body immersed in a fluid is equal to the weight of the fluid displaced. Let's see how this can account for vertical motion in our atmosphere, a fluid. Air is a relatively poor conductor of heat. As incoming solar radiation heats the soil, only the air within a few feet of the ground is heated by conduction. This air expands and its density becomes less than surrounding cooler air. It is bouyed up by this unbalanced force and it begins to rise. Many of these parcels of air may join together and form a larger mass known as a "thermal". Of course, their place must be taken by cooler air moving in from the sides. Once these parcels break away from the ground, they lose their energy source. As they move upward, atmospheric pressure decreases and further expansion occurs. Work is done by the parcels of air on their surroundings as they rise and expand. This energy must be obtained internally. As their internal energy decreases, the temperature of the parcels must drop. Such a change in temperature without the addition or removal of heat is said to be "adiabatic".

How far these parcels rise depends on the surrounding atmospheric conditions, especially temperature. If, as they rise, their temperature remains higher than the surrounding air, they continue to rise and are said to be unstable. On the other hand, if they reach some level where the surrounding air is at the same temperature, there is no longer any unbalanced buoyant force and they stop rising.

If these rising parcels of air are moist, their temperature may drop below the dew point, causing condensation to occur with the formation of clouds.

Considerable energy in the form of heat is released whenever water vapor undergoes a phase change from the gaseous to the liquid state.

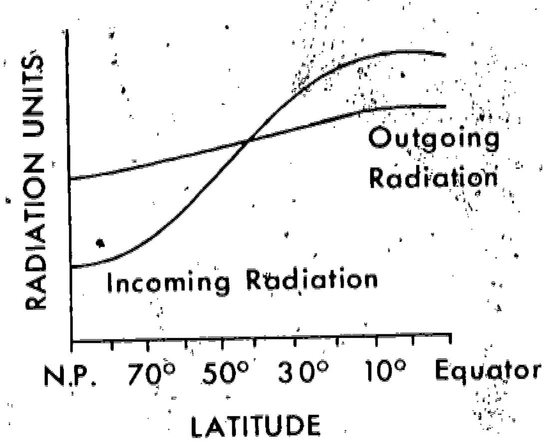
In reality, some turbulent mixing occurs between the rising warm air and the sinking cool air. This tends to establish a temperature lapse rate (the drop in temperature with altitude) that is equal to the adiabatic rate so that by late afternoon there is little tendency for parcels to rise. Often a temperature inversion (increase in temperature with altitude) occurs at night near the ground because the ground is radiating energy faster than it is receiving it. Thus it rapidly cools itself and the air near it.

In order for parcels of air to move in a horizontal direction, there must exist an unbalanced force acting on them. This is provided by pressure gradients that develop between two places on the surface of the earth. Again, solar energy received from the sun provides the driving force. Small scale circulations can develop as a result of daily pressure gradients set up because of the different rates at which land and water masses heat up. The specific heat of land is lower than that of water. In addition, the solar radiation is transmitted deeper into the water and its energy is thereby distributed over a larger mass per surface area. As a result, land masses heat up and cool down faster than water masses. The air in contact with the land masses also is heated more rapidly. It expands and becomes less dense. Being at a lower pressure than the cooler air above the water, a horizontal pressure gradient is formed and sea breezes develop. These blow inland during the day where the pressure is slightly less, seaward at night where the opposite is true. In some places, this circulation exists on a seasonal basis and gives rise to the so-called "monsoons".

On a world-wide scale, we can see that the incoming solar radiation arriving at the equatorial regions is much greater than that arriving at the polar region. The outgoing radiation is more nearly equal in all regions and is only slightly less in the polar region. This means that in the equatorial regions there is a net surplus of heat and in the polar regions a net deficit; only at about 36° latitude does incoming heat equal outgoing heat. Unless a mechanism existed for transporting equatorial heat to the polar regions, the poles would get colder and colder and the equatorial region hotter and hotter.

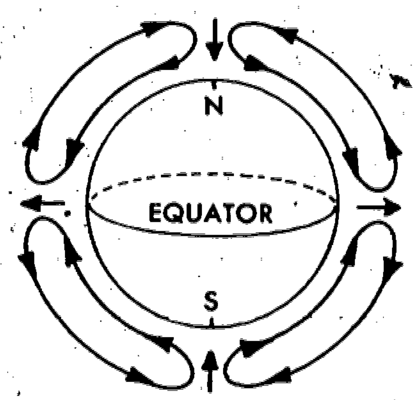
Figure 1

RADIATION BALANCE



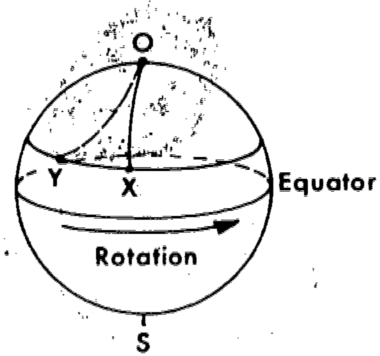
Fortunately, the atmosphere provides the solution. Before we look at the actual picture of what takes place, let's examine some simple possibilities. As the warm surface air of the equatorial region is heated, it becomes less dense and rises, expanding adiabatically. It spreads out moving poleward. While this is occurring, cooler polar air is moving at lower levels toward the equator, taking the place of the warmer rising air. These motions set up a circulation pattern such as shown in figure 2.

Figure 2
"HADLEY CELL"



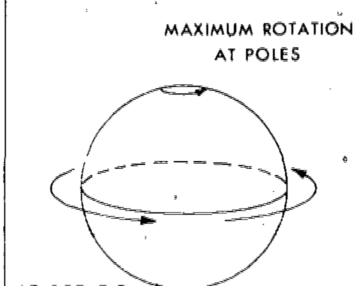
But such a condition does not really exist for we have forgotton to take into consideration the rotation of the earth. The effect of the rotation is to make it appear that a force continuously acts at right angles to shift the direction of motion of any object moving through the atmosphere. In figure 3 below, an object O starts moving from the north pole towards X. While it is moving south through the atmosphere, the earth rotates eastward beneath it. The object O ends up at Y making it appear that a westward directed force was acting

Figure 3
CORIOLIS EFFECT



on it, deflecting it towards the right as it traveled southward. In the northern hemisphere the object will always appear to swing towards the right; in the southern hemisphere it will appear to turn towards the left. This effect is known as the coriolis effect or "force". It makes no difference which way the object initially travels. The magnitude of the effect depends on the speed of the object and its latitude. It is zero at the equator since there is no rotational effect of the earth's surface there. It is maximum in the polar regions. (See figure 4).

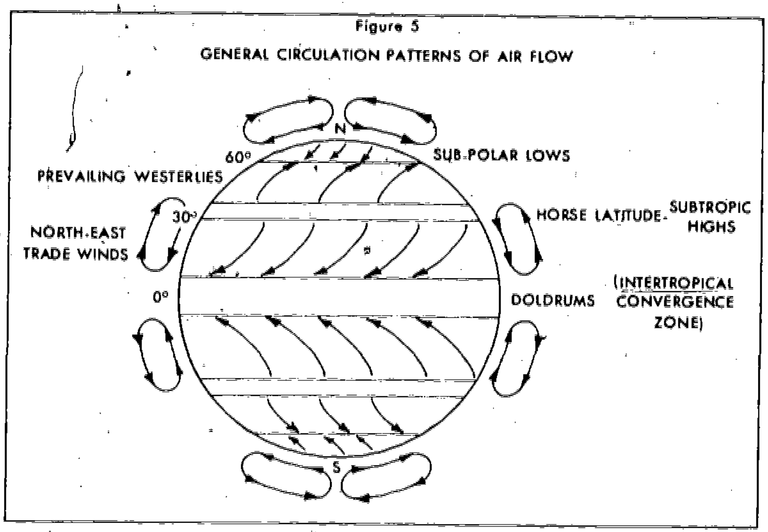
Figure 4



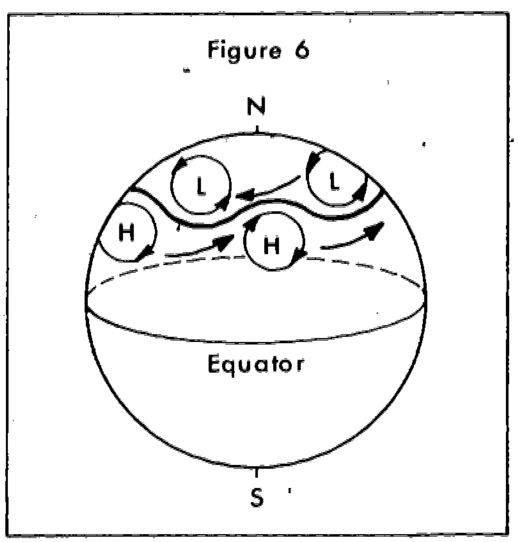
The effect of all this is to modify the original single cell (Hadley cell) pattern and, in fact, make it an impossibility. Aloft, the air would be moving northward and swinging to the right (east); near the surface the air would be flowing southward and swinging west. To accommodate such a pattern, the wind speeds in some regions (polar) would have to become so high that turbulent flow would occur. This would bring about a decrease in velocity to such a point that the law of conservation of angular momentum would be violated.

The generalized circulation pattern that does develop is shown in figure 6 and accounts for much of the weather found in various regions of the world.

This is still an oversimplification since it provides no way to transfer energy from the middle latitudes to the polar regions. This is accomplished by energy transfer between the interfaces of small scale circulatory systems involving air masses of different densities and rotating in opposite directions, the "high" and "low pressure" air masses common in temperate latitudes. These



systems develop along more or less stationary waves of rather large amplitudes and lengths that exist between the polar easterlies and the prevailing westerlies. Associated with this confrontation zone are the jet streams: high altitude ribbons of high-velocity (300 miles per hour) winds winding through the upper troposphere and apparently steering, to some extent, our storm systems.



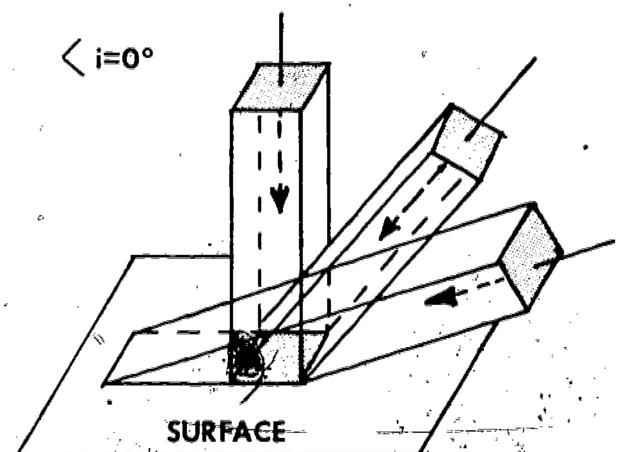
SECTION VIII

VARIATION IN INSOLATION

We have been concerned, so far, with the production of radiant energy by the sun, with its transmission through space to the outer reaches of our atmosphere, and with its subsequent depletion as it passes through the atmosphere on its way to the earth's surface. At the solar surface we found energy being radiated at the rate of 100,000 calories/cm^2/ minute. However, the earth, located about 93,000,000 miles away, offers such a tiny target that only 1.94 calories/ cm^2/ minute arrive on a surface perpendicular to the sun's rays at a point in space just outside the earth's atmosphere. This value is known as the solar constant. As mentioned previously, a calories/cm^2 is often called a <u>langley</u> and the solar constant is often expressed as 1.94 langleys/minute. Since this energy will be spread over a rotating spherical surface, a further reduction by a factor of 4 is required (see section on The Earth - A Solar Collector); this leaves roughly 0.49 langley/minute. Finally, we saw that the atmosphere brings about a further reduction of roughly 50 percent which means that about 0.25 calories/minute or 0.25 langley/ minute arrives on an average on the earth's surface. This value is useful when we are discussing the earth as a solar collector or analyzing the earth-atmosphere heat balance. However, each one of us lives at a specific spot on the earth; we need to know how much energy arrives there and how it varies over the course of a day, season, or year.

The total solar energy received on a surface is called insolation. Insolation at the earth's surface is usually measured in terms of the rate at which energy is received on a horizontal surface. This energy comes from direct solar radiation as well as from diffuse radiation or that scattered out of the direct solar beam. The sum of the direct and diffuse radiation is called global radiation. Diffuse radiation comes from all parts of the sky and accounts for approximately 45 percent of the total insolation on bright clear days; on cloudy days 100 percent of the insolation is diffuse. The insolation at any spot on the earth's surface may range from 0 to a maximum of about 1.4 langleys/minute (on a surface perpendicular to the sun's rays). The factors that affect insolation are latitude, time of day, time of year, cloud cover, atmospheric turbidity, elevation, nearby or distant obstructions, and orientation of the land surface. Let's take a closer look at each one.

Generally, two things determine the amount of radiation available per unit area of ground surface. One has to do with the actual depletion of the solar beam as discussed in previous sections; the other is related to the angle that the



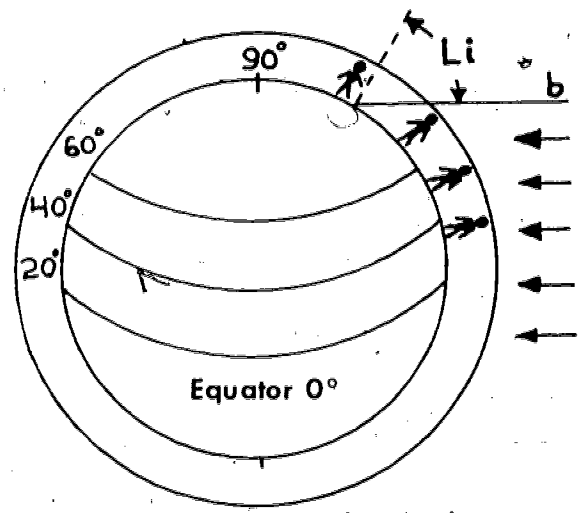
EFFECT OF BEAM ANGLE

VIII-1

sun's rays make with the surface. Consider a beam of radiant energy 1 meter^2 in cross sectional area. When this beam strikes a surface with an angle of incidence ($\angle i$) of 0^{o}, its energy is distributed over an area of 1 meter square. The angle of incidence, $\angle i$, is the angle measured between the incoming (or incident beam) and a line drawn perpendicular to the surface. As the angle of incidence increases, the beam's energy is progressively spread over a larger and larger area as shown in Figure 1. The amount of energy per unit area decreases as the angle of incidence increases. This means that the sun's apparent position in the sky is very important. The higher the sun, the more nearly perpendicular to the surface are its rays. The height of the sun, measured in degrees above the horizon, is known as the solar altitude.

Latitude

Over the course of a year, latitude has the greatest single effect on insolation received at any location. The reason for this is two-fold: the higher the latitude, the more slanting (larger angle of incidence) are the sun's rays to the surface of the ground as can be seen in Figure 2. This means that the energy received per unit area of surface will be less. The second reason can also



Insolation - Effects of Latitude

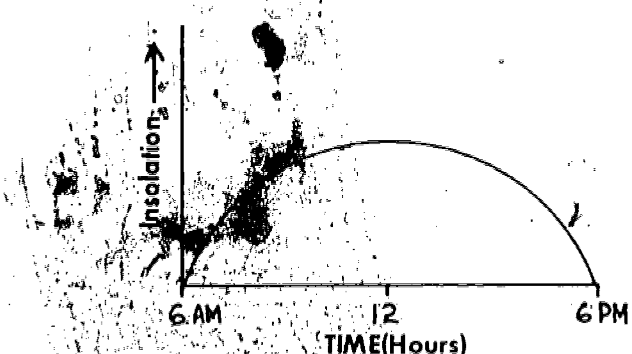
VIII-2

be noted in Figure 2. The path of light rays through the atmosphere to the surface is shorter in the equatorial region (a) then it is at higher latitudes (b). More energy is removed from the beam as it passes through this greater depth of atmosphere. This effect is readily noticed on a daily basis when one can often look directly at the sun at sunrise and sunset without damaging one's eyes. This is not possible at noon because of the greater energy content of the solar beam.

Another effect that this greater path length has is its changes upon the relative amounts of the kinds of radiation arriving on the earth's surface. The original solar beam arriving at the top of the earth's atmosphere consists of approximately 9 percent ultraviolet, 40 percent visible, and 51 percent infrared radiation. If the solar beam passes directly downward through the atmosphere so that its angle of incidence with the earth's surface is 0^{o}, the radiation arriving at the surface will be made up of about 5 percent ultraviolet, 47 percent visible, and 48 percent infrared. If, on the other hand, the angle of incidence is about 80^{o}, the make up of the incident radiation will be about 0.5 percent ultraviolet, 41 percent visible, and 58.5 percent infrared. These values assume reasonably clear unpolluted air, with a precipitable water vapor pressure of .2 cm.

Time of Day

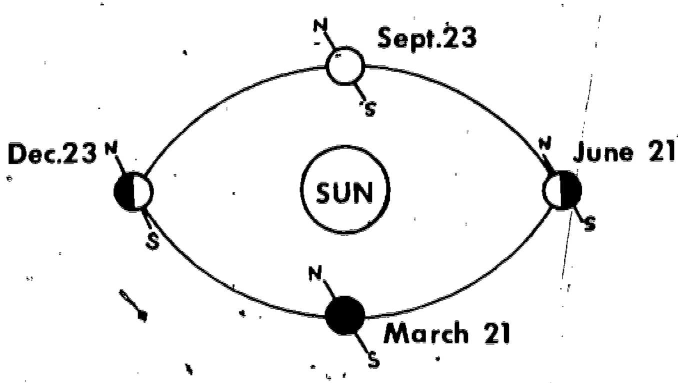
The variation in insolation received with time of day is related to the same two factors discussed above. At sunrise, the angle of incidence of the sun's rays is nearly 90^{o}. At solar noon, it is minimal. Insolation measured on a horizontal surface plotted against time of day is shown in Figure 3. As might be expected, the general shape of the graph follows closely that showing the sun's altitude plotted against time of day.



VIII-3

Time of Year

In addition to the two factors already discussed, the sun's altitude and variable path length, yearly variations introduce changes in the length of day as well. The earth's surface in the northern hemisphere receives radiant energy for longer periods in summer than it does in winter. The explanation for all of these yearly variations is related to the fact that the earth's rotational axis is tilted 23 1/2^{0} with respect to a line drawn perpendicular to the plane of the earth's orbit about the sun. As a result, in the northern hemisphere the sun



VIII-4

appears highest in the sky at solar noon on June 21 and lowest on December 22, (Figure 4). A fourth factor must also be considered. The earth's path about the sun is an ellipse. This means that the distance between the earth and the sun varies from about 91.5 million miles in December to 94.5 million miles in June, making the earth closest to the sun during our winter. There is a corresponding variation of about 3.3 percent in the solar constant. As a result, at a latitude of 40^{0} a slightly higher insolation value is measured on a surface normal to (at right angles to) the sun's rays at noon in March than at noon in July.

Cloud Cover

Cloud cover means the extent, height, thickness, and type of clouds covering the sky. Cloud cover brings about the greatest day to day variation in

286-998 O - 79 - 4

insolation at any particular locality; it is also the least predictable of any of the variables. It is the variation in cloud cover that causes the large differences in daily or monthly insolation values between places of similar latitude. It is often the most important factor in determining seasonal variations. For example, United States weather service data shows that in January the percent of possible sunshine varies from 84 percent in Yuma, Arizona to about 19 percent in either Oswego, New York or Portland, Oregon. Since these cities differ in latitude by about 14^{o}, such a difference would result in differences in insolation rates of roughly 34 BTU/ft^2/hr or only 0.09 langley/minute. Yet records show that much larger differences in the mean daily insolation for the month of January exist between the cities (on the order of 1,000 BTU/ft^2/day).

Atmospheric Turbidity

Haze, smoke, fog, smog, dust, etc., all contribute to the turbidity of the atmosphere. Turbidity is the reduction in the transparency of the atmosphere caused by the scattering or absorption of visible light by such particles. Pollution around large cities can decrease insolation by as much as 20 percent compared to surrounding rural areas. In addition, turbidity alters the percentage of ultraviolet, visible, and infrared radiation received in much the same way that increased path length does. The amount of ultraviolet and visible light received decreases and the amount of infrared radiation increases with rise in turbidity.

Altitude

Increased altitude increases the energy content of the direct solar beam and therefore the insolation received. This is true because the density, and therefore the number of particles, decreases with altitude. Fewer particles produce less absorption and scattering of the incoming solar beam. Mountain climbers are well aware of the increased likelihood of sunburn and usually take preventive action to avoid it.

Obstructions

Nearby obstructions such as trees and tall buildings can block off the direct rays of sunlight during part of the day. Even if they do not block off the direct sunlight, they may interfere continuously with the diffuse radiation that would be received from certain areas of the sky. In hilly or mountainous sections, the horizon may be so altered as to materially reduce the available insolation.

Orientation of the Land Surface

We have indicated that most insolation data is for a horizontal surface. If the land surface or surface of the solar collector slopes, the amount of insolation will vary. In the northern hemisphere, south-facing slopes receive more insolation; north-facing slopes less. Maximum insolation occurs when the surface is normal to the sun's rays. The effect of this is often noted in spring when the snow melts first from steep south-facing slopes or embankments.

All of these factors operate to produce considerable variation in the mean daily solar radiation available in different regions throughout the United States. Actually, the amounts closely follow the distribution of cloudiness.

The Pacific northwest and the northeastern states share the unenviable status of being the cloudiest portions of the nation. On an annual basis, both portions receive mean daily global radiation values (on a horizontal surface) of about 300 langleys/day. This contrasts with the sunniest portion of the country, the southwest, which receives about 500 langleys/day. Understandably, the southwest is an attractive region for solar energy research and applications.

Seasonally, the southwest receives on the average about 300 langleys(ly)/day in January, 625 ly/day in April, 675 ly/day in July, and 425 ly/day in October. The southeastern states during the same months receive between 200-300 ly/day, respectively. (These values, as for all the regions defined here, are representative of the region as a whole. Individual locations typically experience deviations from the regional average, depending on their relative location.) In the northeast, January radiation amounts approximate 130 ly/day, April, 375 ly/day, July, 500 ly/day, and October, 225 ly/day. During the same months, the northwestern states experience 125 ly/day, 450 ly/day, 625 ly/day, and 250 ly/day, respectively.

The variation in mean daily solar radiation on a statewide basis can be seen by examining the figures for New York State. For the annual period, the mean daily global solar radiation (on a horizontal surface) is approximately 300 ly/day for the state. Central and eastern Long Island experience the maximum with about 315 ly/day while the mountainous Adirondacks receive the least, 285 ly/day. These values are 1970 to 1978 averages based on available solar radiation data for twelve state locations.

In the late fall and winter months, Lakes Erie and Ontario are sources of considerable lake-effect cloudiness over western and central sections of the state, and occasionally even over eastern sections. In December, most of upstate New York averages between 75 and 100 ly/day while the Hudson River Valley and Long Island receive about 100 ly or so. January sees an increase of about 50 ly/day statewide. December normally is the month of least solar insolation while July is usually the sunniest month. While the areas adjacent to the Great Lakes, the Hudson River Valley, and eastern Long Island average greater than 500 ly/day in July, the bulk of upstate New York and west-central Long Island experience from 473 to 500 ly/day.

SECTION IX

MEASUREMENT OF INSOLATION

In the last section, factors that affect insolation and its general distribution were discussed. Nothing was said, however, about how insolation is measured. Actually, several basic measurements can be made. One of the most simple is merely a record of the duration of sunshine; the minutes of sunshine received per day as routinely measured by National Weather Service stations. There are about 2,000 such stations throughout the world recording this information. Global radiation, the total of direct and diffuse radiation, is usually measured on a horizontal surface with a pyranometer. About 700 worldwide stations record global radiation; of these some 70 are United States Weather Service Stations in this country. Direct solar radiation is more difficult to measure; a sun-tracking pyranometer, or pyrheliometer, is required. Diffuse solar radiation, a measure of the scattered radiation received from the sky, is measured with a shaded pyranometer; again, data is usually obtained for a horizontal surface. Finally, selective measurements of diffuse and/or direct radiation for defined wavelength intervals are made using selective filters in conjunction with the equipment previously mentioned.

Each of these instruments will be briefly described:

<u>Pyranometer</u>: The pyranometer or solarimeter is usually mounted horizontally and measures the global or total radiation. There are several types, although the thermopile type is probably the most common. A thermopile is a group of thermocouples connected in series and mounted on a blackened receiving disc. A thermocouple is a junction between two dissimilar metals such as copper and the alloy constanstan.

When the junction is heated, a small electric current is produced. A second reference junction is attached to a white or silvered ring of equal area that remains at ambient temperature, since most of the radiation falling on it is reflected. The current thus generated can be calibrated in terms of the radiant energy received. The thermopile is sensitive to the solar spectral range of .29μ to 3.0μ, which contains most of the energy of the sun as received since its response time is on the order of several seconds. The thermopile sensor is usually sheltered within a hemisphere of glass; data is recorded on a recording potentiometer. Major commercial suppliers are Eppley, Kahl, and Spectrolab in the United States, Kipp and Zonen in Holland, Groiss in Australia, Mashpriboringtorg in the U.S.S.R. and EKO in Japan.

Silicon solar cell pyranometers have a response time of less than a millisecond. (See the section on solar cells for an explanation of how they work). However, they have a limited spectral response range, with maximum intensity recorded at .9μ and an upper limit of 1.1μ. Solar radiation extends further, to about 2μ, although its maximum intensity is at .5μ. Yellow Springs Instrument Company and Matrix, Inc. supply these types of pyranometers. They also offer the best possibility for the do-it-yourself builder; they are relatively cheap, of simple construction, and, with proper calibration with a commercial unit, give satisfactory results. Other types include bimetallic strip pyranometers such as those supplied by Casella Company in the United Kingdom and R. Feuss in West Germany. These work through unequal thermal expansion on two sides of a bimetal strip which in turn controls the position of a recording pen on a moving chart. In the United States, the older model of the Eppley pyranometer (50 junction) and the newer Model 2 (precision spectral pyranometer) comprise the overwhelming majority of pyranometers in use today. Accuracy of the newer precision models is within 1 or 2 percent. To selectively measure the energy contributed by specific wavelength bands, glass filters may be placed over the pyranometer.

Normal Incidence Pyrheliometer: These are used to measure direct solar radiation. This requires that only energy from the sun's disc be allowed to reach the sensor. This is accomplished by mounting the sensor, a thermopile for example, on the bottom of a blackened tube provided with light stops. The ratio of the cylindrical tube length to tube diameter should be about 10 to 1. This limits the view of the sky and sun to about 5^{o} and eliminates most of the diffuse radiation. The instrument is then mounted on a motor driven heliostat (a device that follows the sun). The axis of the heliostat is readjusted several times a week as the declination of the sun changes. Types and makes of pyrheliometers include: Angstrom electrical compensation; Abbot silver-disc; Michelson bimetallic; Line-Feussner iron-clad; New Eppley (temperature compensated); Yanishevsky thermoelectric; Moll-Goczynski solarimeter by Kipp and Zonen; and the old non-temperature compensated Eppley. Glass filters may also be placed over the pyrheliometer sensor to selectively measure the energy contributed by specific wavelength bands.

Shaded pyranometer: The measurement of diffuse radiation can be performed by a pyranometer which is shaded from the sun's direct rays. Shading of the pyranometer is accomplished by a disc made to move with the sun so as to always cast its shadow on the pyranometer, or by means of a shadow ring. Because of the trouble in keeping the shading disc in proper adjustment and the expense of an equatorial mount, the shadow ring is the more popular of the two devices. But the price paid for using the shadow ring is the necessity of introducing a correction for the part of the diffuse radiation which is cut off from the sensor by the ring. As the declination of the sun changes with time, the ring must be moved along an axis oriented parallel to the earth's axis so as to always shade the pyranometer from the direct radiation.

SECTION X

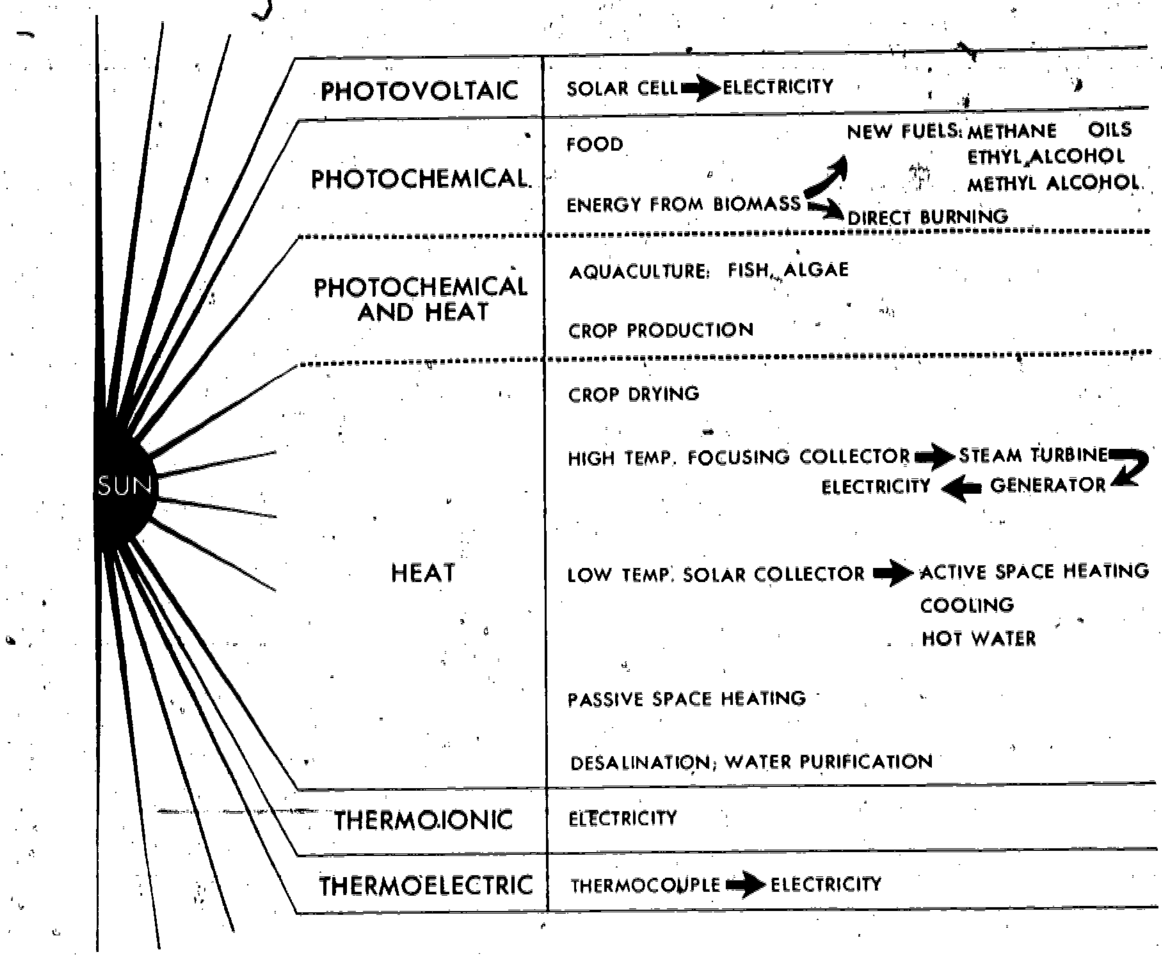
USES OF SOLAR ENERGY

This section describes uses or potential uses of solar energy, many of which will be treated in greater detail in subsequent sections. The direct use of solar energy is not new. For thousands of years, ancient peoples relied on the sun's energy to evaporate small pools of brackish water so that they might collect the salt. In 1872, a large solar still was built in the Chilean desert to supply 6,000 gallons of pure water per day from salt water. Solar cookers were built and used in India in the 1880's. Michael Faraday discovered the principle of solar cooling in 1824. Small steam engines were powered by solar energy as early as 1878; a 50 hp engine was used in 1913 to pump irrigation water in Egypt. Solar hot water heaters were popular in our southern states in the 1930's. However, the direct use of solar energy never really caught on for there were always cheaper, alternate energy sources available; wood, water power, or fossil fuels. It wasn't really that these sources were cheaper than the sun's energy which, after all, is free. Rather, the costs of building devices to utilize the sun's energy were greater than the costs needed to utilize the other sources that were available.

Today the picture is beginning to change. Other sources of energy are dwindling and their costs are rising at a rate of 10 percent or more a year. Once again, we need to take a closer look at the inexhaustible energy of the sun and determine how it can be put to practical use to supply an ever-increasing percentage of our energy needs.

There are several energy conversion processes by which we can use the radiant energy provided by the sun. First, the energy can be absorbed by collectors and converted directly into heat energy. A second method involves direct conversion of radiant energy into electricity through a process known as the photovoltaic effect. This involves the use of solar cells so familiar to the space program as energy sources on space vehicles. A third process is photochemical and involves plant photosynthesis. Here nature has been far more successful than man. Other possible energy conversion processes include the photoelectric effect, whereby electrons are ejected from the surface of metals by radiant energy; the thermionic effect, which forms the basis of the operation of vacuum electron tubes; and the thermoelectric effect or Seebeck Effect, used now mainly for temperature measurement (the thermocouple). Large scale application of these last three processes for solar energy conversion does not seem practical at this time, although efficiencies are being improved.

USES OF SOLAR ENERGY



Solar Heat Energy

Let us first consider heliothermal conversion or the conversion of the sun's energy directly into heat. This can be accomplished by solar collectors in two general ways. Flat plate collectors may trap energy that falls upon a surface as previously described in the section on "The Sun - A Solar Collector in Space". Here temperature rise is low to moderate. A second type of collector is the focusing collector which can produce very high temperatures, as much as 3,500^{o}C. Each of these will be discussed in detail in later sections.

Heat energy provided by the sun is being used in a number of practical ways. It can be used to provide space heating through either active or passive solar systems. An active system is usually made up of collectors, an externally powered heat transport system, an energy storage medium and system, and the necessary controls to maintain efficiency. In a passive system, the building itself is architectually designed to serve as the collector and storage system with maximum use being made of building and site orientation, landscaping, and other passive means to minimize dependence on secondary energy sources.

In many parts of the country auxiliary heat will be needed. While it might be possible to design a solar system to supply 100 percent of the heating needs, cost effectiveness studies have shown that economically this may not be feasible. In the Northeast, solar energy can economically supply roughly 60 percent of the heating needs of new homes. In such cases, solar assisted heat pumps might be the answer. Since their cycle is reversible, they can be used not only for heating in winter but for cooling in summer as well. Basically a heat pump is similar to a refrigeration unit in that it pumps energy from one place to another. But instead of removing energy from inside the refrigerator and pumping it into the kitchen via its cooling coils, heat is pumped from outside the house into the living space itself.

Solar heat can also be used directly to cool a building through a process known as absorption-desorption cooling. Over the years a number of gas burning refrigerators have been on the market that make use of this sytem of cooling. Similar systems using solar energy as the heat source have been designed. The major problem with these systems is their requirement for water temperatures from the solar collector of at least 195°F. Most flat plate collectors operate at a lower temperature than this. Nevertheless the use of solar heat for cooling seems to offer economic advantages over conventional methods. One reason is that solar energy availability is at a maximum in those places and at those times when cooling is most needed, that is, during daylight hours in summer in the western and southern sections of our nation.

In addition to heating and cooling our homes, solar energy can be used to provide us with hot water. Many commercial units are now on the market. In the north, supplementary heat will be required during the winter months. Throughout much of the country, however, solar hot water heating is already competitive with electric hot water heating.

Other uses of heat produced by solar energy include crop production in greenhouses, the desalination and purification of water, and agricultural or industrial drying. Focusing collectors have been employed to attain very high temperatures in the so-called solar furnaces being used for experimental work involving certain chemical and metullurgical operations.

Solar Electricity

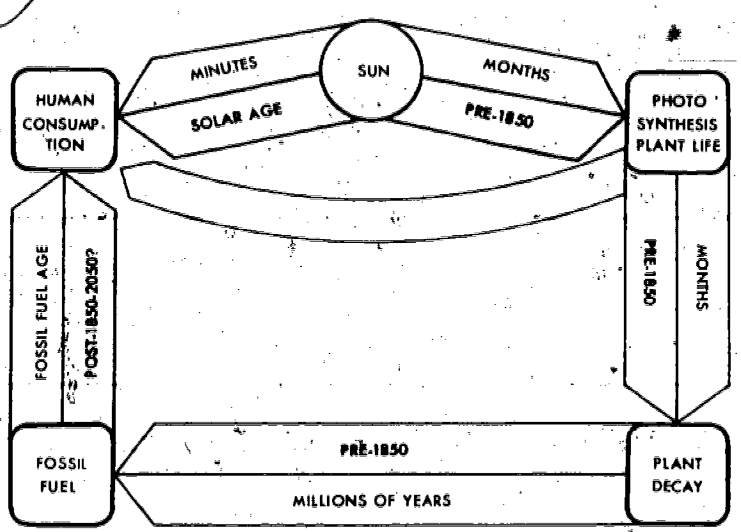
Electrical generation has been accomplished in several ways. One involves the use of focusing collectors to produce steam from water. The steam is then used to operate a turbine which in turn drives an electrical generator. A second method, which has found widespread use on space vehicles, involves the photovoltaic process making use of solar cells. Both of these methods will be described in detail in a following section.

Photosynthesis

No man-made photochemical process has yet been found to rival nature's photosynthesis where carbon dioxide and water are combined in the presence of chlorophyll and sunlight to form carbohydrates while releasing oxygen. It is the stored energy in carbohydrates which can be obtained in various biomass conversion processes which we will be discussing in a separate section later.

In summary, as man turns more to solar energy he returns to the ultimate source of nearly all of our energy, the sun. This can be illustrated in the flow chart below.

ENERGY FLOW & RECOVERY TIMES



Before 1850, man's main source of energy came from burning the wood produced by a photochemical process requiring several months or years. But 1850 more or less marked the development of fossil fuel burning technology, thus raising the energy recovery time to millions of years. As the depletion of fossil fuels takes place, we must again return to the energy conversion processes with minimum recovery times: direct solar heating and cooling, electric production by way of photovoltaic conversion, and biomass conversion.

SECTION XI

SPACE HEATING - PASSIVE SOLAR SYSTEM

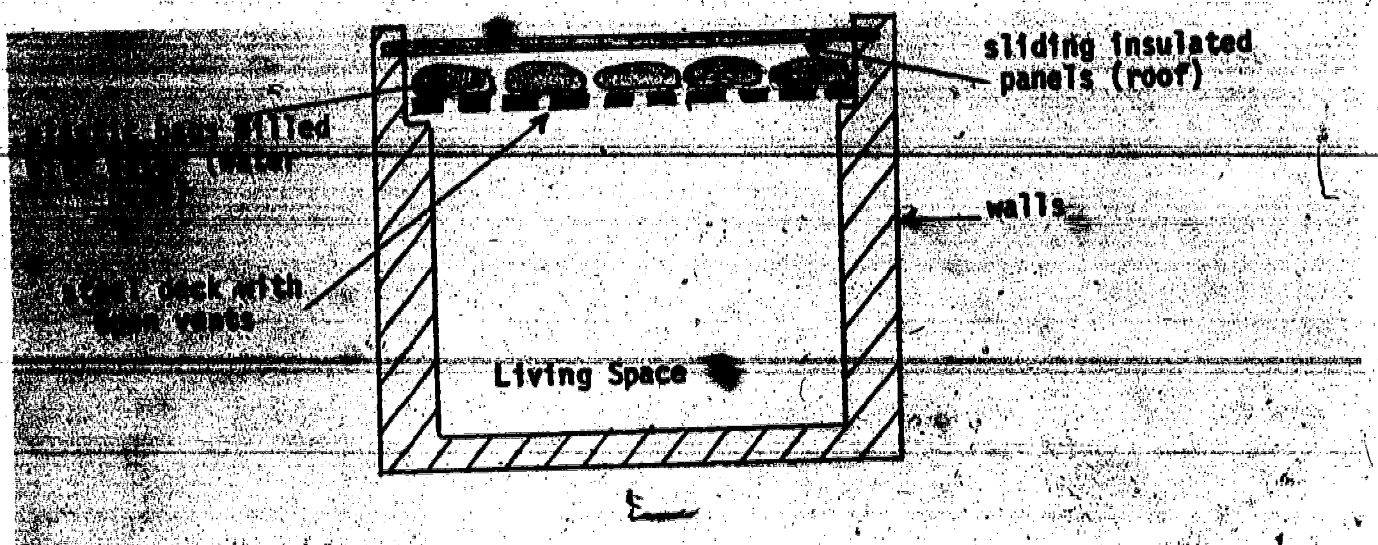
In a passive solar heating system no external energy is used to transfer heat from the solar collector to the heat storage unit; they are one and the same. This definition of passive heating does not really convey a true appreciation of the many facets of passive solar heating. Actually, most homes use passive solar heating to some degree, whether or not it is intentional. South-facing windows in winter admit sunlight which is absorbed as heat energy by the objects within the room. Roofs to some extent act as solar collectors (attics are often warm even in winter when the sun is shining). Roof overhang also permits the low slanting rays of the winter sun to enter the windows while keeping out the rays of the higher summer sun. Deciduous trees planted near the house on its south and west sides lose their leaves in winter and permit extra energy to fall upon the house at just the time it is most needed. A coniferous windbreak located some distance to the north or west of the house cuts down the velocity of the winter wind and thereby reduces heat losses from within the house. These are the kinds of things to be included in the concept of a passively heated solar house.

Careful planning must go into all phases of the location and design of a passively heated home. Site location is important. A south-facing slope is usually warmer than a nearby valley or the crest of a hill. Vertical windows on the south side of the home admit winter sunshine; these are especially effective if the sunlight falls upon a massive dark colored interior wall that can act as a solar collector. A concrete or stone patio on the south side of the house can similarly act as a heat absorber of sunlight. In summer this can be shaded by deciduous trees to help keep the house cool. Since there have been many good books written on this subject, all we shall do is mention briefly some of the specific designs that have been proposed for passive heating.

Among the most noteworthy is the Trombe Wall, designed by and named after the famous French pioneer in solar heating. Its basic design is shown below:

The key to this passive system is the massive interior rough black concrete wall. In winter the vent and windows are kept closed while the sun's rays shining through the south glass wall strike the concrete wall and are absorbed. Part of the heat is immediately reradiated as infrared and trapped by the glass. The air in contact with the wall is warmed, natural convection distributing heat as shown in the sketch. The wall stores enough energy to heat the house overnight. In fact, nearly three-fourths of the entire winter's heat requirements can be provided by this passive system. In summer, the vent at the top of the south window is opened as well as the rear window. The heating of the wall sets up convection currents that move the warm air up and out of the front of the building while cooler air flows in and keeps the living quarters cool.

Another passive system is the Sky Therm System, designed by Harold Hay. This is shown below:



Sky Therm System

Water beds supported on a strong steel deck act as the collector and storage system of thermal energy. In winter, the sliding insulated panels are opened during sunny days and closed at night. While energy is radiated into the room from the ceiling during night and day, the closed panels prevent radiation losses to the sky at night. In summer, the roof panels are opened at night to permit cooling of the water by radiation. They are closed during the day and cool water absorbs energy from the house. Other designs somewhat similar to the Sky Therm design, but less complex, involve shallow solar pools located on the roof.

A third passive system makes use of the fact that the temperature of the earth does not fluctuate rapidly like the air temperature, nor does it reach such extreme temperatures in most areas. Here much of the house is covered by earth. Again, south facing windows admit winter sunshine for its heating effects. The

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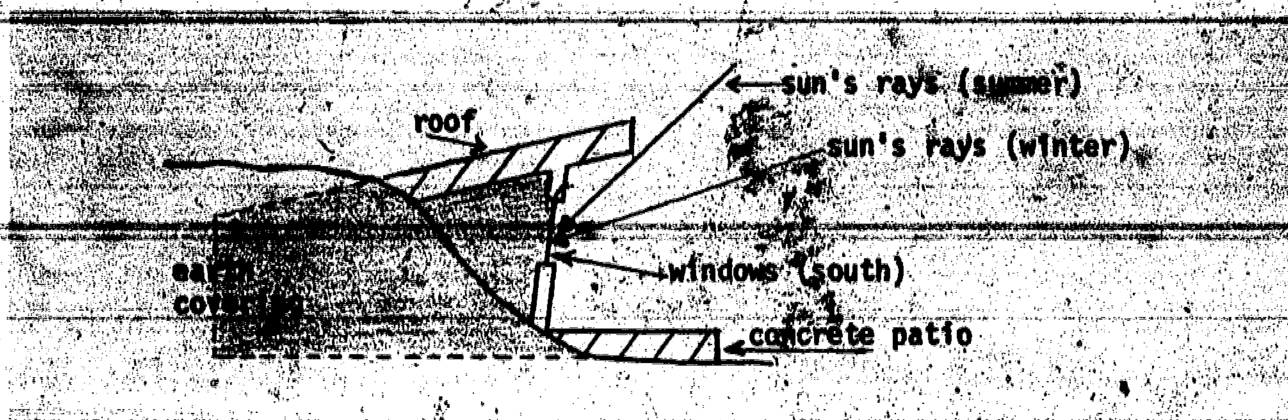
walls of the house are made of concrete and insulated externally where they are in contact with the soil, thus acting as the heat storage unit. This system, as shown below, is not unlike the pit greenhouses that have been used for many years:



In the passive systems described above, auxiliary heat is likely to be needed in all but the most southern regions. However, considerable savings in energy can be realized by making use of many of these passive heat collecting techniques even if the house is to be heated by some other means.

SECTION XII

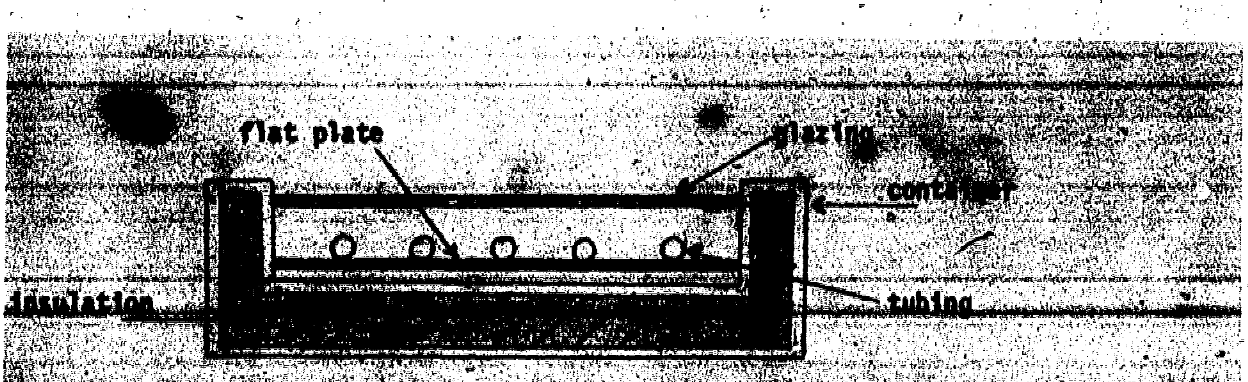
SPACE HEATING - ACTIVE SOLAR SYSTEM

The Solar Collector

In section 3 "Earth, A Solar Collector in Space", the earth-atmosphere system was examined in terms of a solar collector. The various components of a solar heating system were discussed: the glazing, the collection plate, the energy-transport system, the thermal storage system, and the enclosure. The general function of each component was described. In this section we shall look more closely at the specific details of the solar collector unit.

The Solar Collector - Flat Plate

Many different designs have been developed for flat plate collectors. Basically, the flat plate collector is a device which absorbs the energy falling upon it and transfers this energy to the transport medium. No attempt is made to concentrate the sun's energy on a smaller area; as a result, the maximum operating temperature of the fluid in a flat plate collector is usually less than 65°C (150°F). The collector consists of an enclosure, insulation, glazing, and a flat plate and/or tubing to carry the heat transfer medium.



Schematic Diagram of Cross Section of Flat-Plate Collector

MATERIALS USED IN FLAT PLATE COLLECTOR CONSTRUCTION

COMPONENT	MATERIALS USED	COMMENTS
Container:	Metal (Aluminum, galvanized steel) Fiberglass Plastic	Lightweight, durable. Many plastics deteriorate rapidly on exposure to ultraviolet radiation.
	Wood	May deteriorate because of high stagnation temperature (350°F) and moisture condensation.
(There is no standardized size for single units: a 4 x 8 ft. unit is difficult for two persons to handle: 4 x 4 ft. units are often used. 2 x 3 ft. units may be used to take advantage of local availability of this size sheet metal.)		
Insulation:	Fiber glass (glass wool)	Has relatively high insulating value, stable.
	Polyurethane foam	Expensive, deforms over 160°F.
	Styrofoam	Flammable.
(Two to four inches of fiberglass insulation should be used.)		
Glazing:	Glass (many types available)	Probably best, but costly and breakable.
	Low iron glass (looks blue on edge)	.88 transmittance, common.
	Water white crystal (ASG)	.92 transmittance, costly.
(Glass thicknesses should be 1/8" or 3/16"; double glazing with one inch air space needed in colder regions or if temperatures over 160°F are desired.)		
	Fiberglass ("Filon", "Kalwall")	Good, but some loss of transmittance with ultraviolet aging (special ultraviolet resistant types available at higher cost.)
	Polycarbonates ("Lexan")	Good, but very expensive.
	"Mylar", "Tedlar" sheeting	Reradiate infrared; mylar undergoes ultraviolet degradation.
	Polyethylene Film	Poor, short life (1/2 yr.) transmits up to 70% infrared (this represents a heat loss.)
Flat Plate:	Copper	Probably best.
	Aluminum	Corrosion problems if contact with other metals.
	Steel, galvanized	Poorer heat conduction, may rust eventually.

COMPONENT	MATERIALS USED	COMMENTS
Tubing:	Copper Aluminum Plastic	Best. Possible corrosion problems. Poor heat transfer, low temp. use.
Paint:	3M "Nextel" or "Black Velvet" Flat Black	.98 absorptivity with 93. emissivity, expensive. Should stand 400°F
Selective Coating:	Black Chrome Nickel Black Black Copper Oxide	Best, durable, .90 absorptivity and .15 to .35 emissivity, but very expensive.
(Selective coatings increase efficiency dramatically when there is a large temperature difference between the collector plate and outside air. For low temperature collectors the extra cost is probably not warranted.)		
If the heat transfer medium is air instead of liquid, then no tubing is required and just the flat or corrugated sheet, with or without baffles, is used.		

Some plate/tubing designs:

Round Tubes Bonded to Plate

Flattened Tubes Bonded to Plate

Tubes Bonded to Corrogated Plate

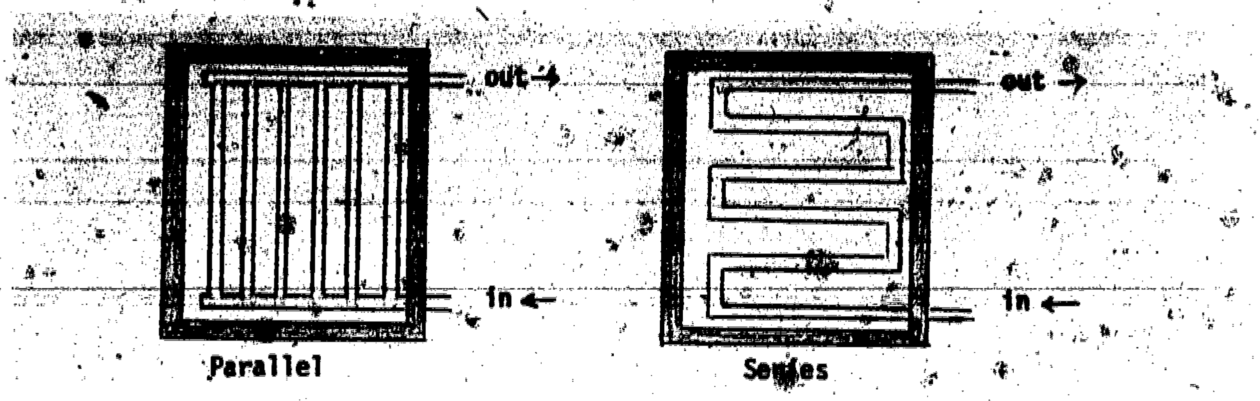
Tubes Integral with Plate

Corrogated Sheet Riveted to Plate

Water Flowing in Open Channels

When using thick copper tubing, the distance between tubes should be 8" - 10"; thin copper tubing, 3" - 4" apart. Equivalent sized aluminum tubes should be spaced closer; plastic tubing must be very close. Normally 1/2" or 3/4" copper tubing is used with 1 - 1 1/4" headers.

The tubing may be connected in parallel or series as shown below. The inlet is always on the lower side.

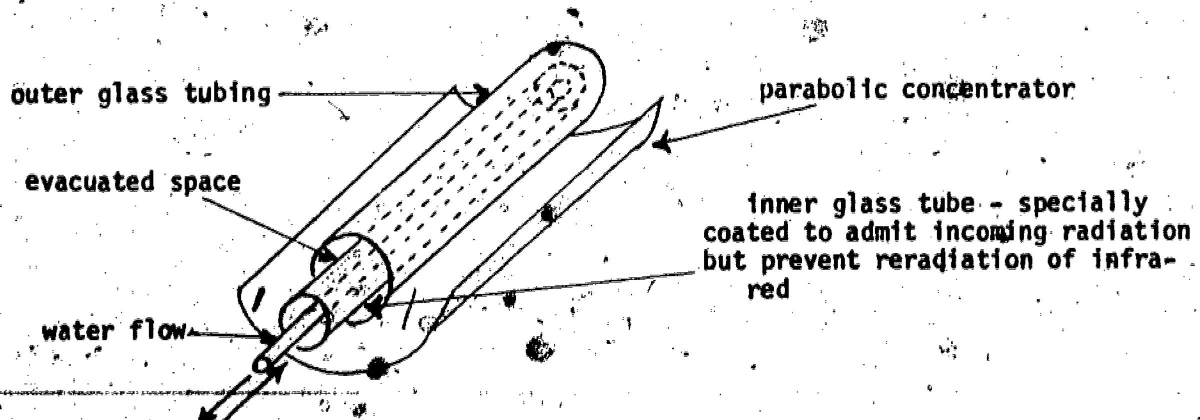


Each type of connection has its advantages and disadvantages; the choice is not critical.

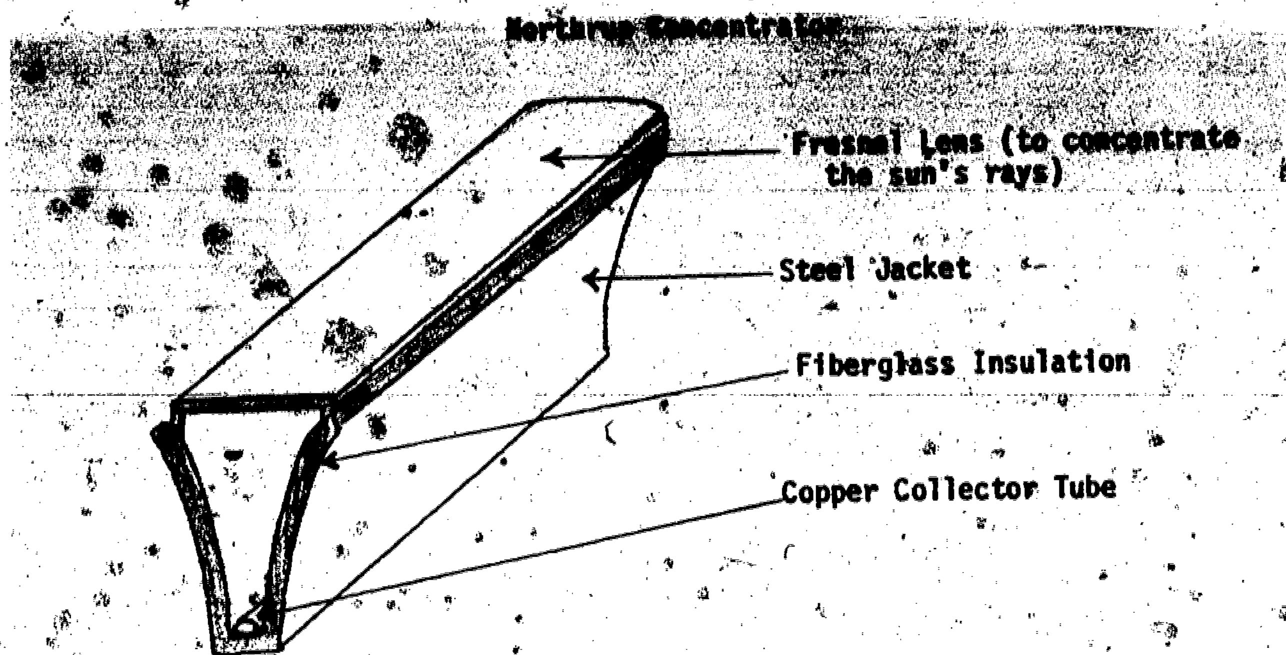
The Solar Collector - Evacuated Tube Concentrator

There is one other type of collector that falls somewhere between the focusing reflectors discussed in the previous section and the flat plate collectors described above. It is the evacuated tube concentrator manufactured by several companies. Its purpose is to provide heat energy for space heating or domestic hot water at a higher temperature than the flat plate collector.

Owens Corning Concentrator



A different concentrator design is shown below; it has an even higher efficiency, up to 70%, and operates at a higher temperature.



This unit is furnished with tracking equipment to follow the sun. The Fresnel Lens focuses the sun's rays on a small diameter tube in the bottom of the insulated collector.

The surface area required of the solar collector varies with geographic location. A very rough rule of thumb is a one to three ratio of collector area to living space. In the colder regions of the country it is still not economical to rely on solar heat for more than 50 percent of the total space heating required. Domestic hot water heating by solar energy is competitive at present with electric hot water systems in much of the country. Solar collectors now cost roughly $\$10/\mathrm{ft}^2$; entire systems $\$20$ to $\$40/\mathrm{ft}$. Costs, however, are subject to rapid change. Systems integrating solar cooling with solar heating require the concentrator-type collector because of the need for water temperatures of 93°C (200°F) or more.

SECTION XIII

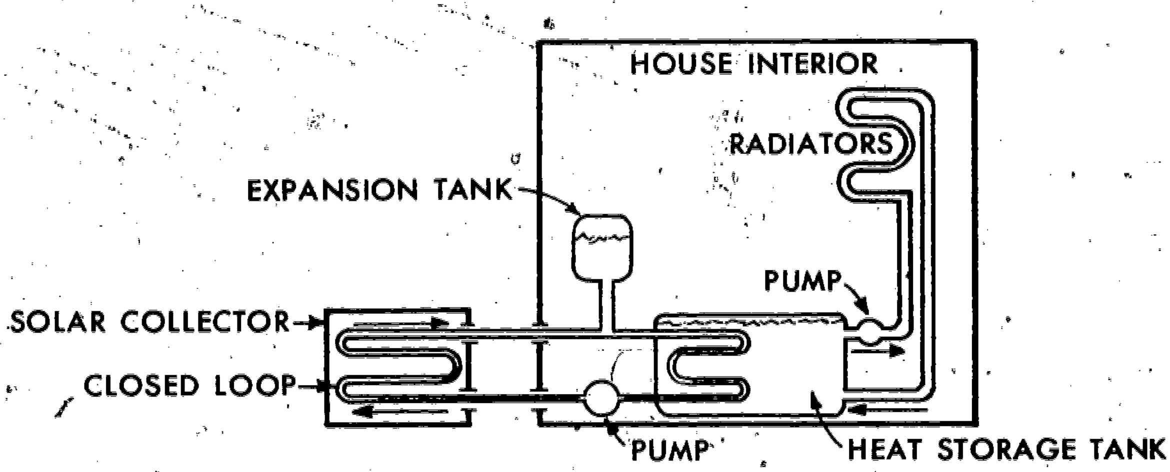
SPACE HEATING - ACTIVE SOLAR SYSTEM

The Transport and Storage System

Transport Medium

The heat generated in the solar collector must be transferred to where it will be utilized. This requires the use of a fluid and is accomplished by natural or forced convection. The two fluids used are air or water. Both fluid systems have their pros and cons: the air system is more easily built and installed by the homeowner while the liquid system is the one usually manufactured. The water systems interface more easily with domestic hot water systems and use cheaper, more compact heat storage (water tanks). The liquid systems are generally more efficient; however, the operating temperature of the heat transfer medium must be higher 72^{o} to 82^{o}C (160^{o}F to 180^{o}F) if it is to be used directly in radiators or convectors, while air temperatures of 27^{o} to 38^{o}C (80^{o}F to 100^{o}F) are adequate for forced air systems. It is easier to find leaks in liquid systems but, at the same time, they are far more damaging. Liquid systems require simpler control devices but are more likely to be plagued with corrosion problems requiring expensive repair.

In colder sections of the country, where freezing temperatures are encountered, the system must be protected against freezing. Systems can be designed for rapid draindown from the collectors when temperatures reach a certain minimum level or when the system is not in use. A more common method of protection involves the use of an anti-freeze mixture added to the water. Most anti-freezes have a base of ethylene or propylene glycol, with various additives to prevent corrosion. Many anti-freezes are toxic and must not be allowed to contaminate drinking water. The amount of anti-freeze needed in very cold climates adds considerable expense to a large system; in this case it is often advantageous to couple the fluid in the solar collector to fluid in the storage system by means of a heat exchange unit. The need for costly anti-freeze is then greatly reduced.



Heat Storage

Since the sun does not shine on the collector 24 hours a day, 365 days a year, provision for heat storage must be made. Heat can be stored as sensible heat, in which case the temperature of a large mass of material is raised or it can be stored as hidden or latent heat. Latent heat is stored by causing a material to undergo a phase change (for example, from liquid water to steam), or to undergo certain reversible reactions involving hydration (the adding of water molecules to crystals). The advantage of latent heat storage is that the amount of energy stored per unit mass of the substance is relatively high; therefore, storage volume is greatly reduced. There are still many problems that have not been solved for latent heat storage. Most systems now use sensible heat storage.

In a water system sensible heat storage usually consists of a large insulated tank. The water is treated chemically to adjust its pH to a range of 8.0 to 8.5 to prevent corrosion of metal parts in the system. Water has a high specific heat compared to most substances and therefore makes a good sensible heat storage medium. The water may be used both as the heat transfer fluid and the heat storage medium. The size of the storage tank depends on local conditions and the amount of auxiliary heat available. The tank should be large enough to provide heat during the night; whether it should be capable of supplying heat for two, three, or five consecutive cloudy days is an individual matter. A general rule of thumb is that the tank should supply 15 BTU/^{o}F of storage for every one square foot of collector; this is approximately two gallons of water/square foot of collector.

In an air system, storage is accomplished by means of rock or pebbles. Rock has a specific heat approximately 1/5 that of water with a density (weight/volume) three times water. Since rocks are solid, heat transfer must occur by conduction rather than by convection, but since the conductivity of rocks is not very high they must be rather small in size to give a good surface area to volume ratio. Usually rocks one to two inches in diameter are used. Since the space between the rocks does not contribute to heat storage, the total volume of the rock bin must be slightly over two times that of an equivalent water tank. For example, a 1,000 cubic foot tank of water (6,000 gallons approximately) would be equivalent in storage to a rock pile of about 2,250 cubic feet (a pile roughly 20 feet by 18 feet by 6 feet).

Rocks are not necessarily cheap and may not be available in many areas. They must be clean or the air filters will keep clogging up. Usually they are non-corrosive, and once in place need not be replaced or serviced in any way. The rocks are often supported by a strong metal grill at the bottom of a vertical cylinder. Air from the collector enters the top and is forced to the bottom of the pile where it is returned to the collector; bypasses are provided to pass the hot air to the heating system directly if needed. Horizontal rock bed systems may also be used. A general rule of thumb is that 60 pounds of rock should be provided for every square foot of collector area.

A few latent heat storage systems have been constructed. As mentioned previously the advantage is the much smaller storage volume required. For example, a system using the salt hydrate, Glaubers salt ($Na_2SO_4 \cdot 10H_2O$), would require only a closet sized space, about 115 cubic feet, to provide the same heat storage as 1,000 cubic feet of water or 2,250 cubic feet or rock. Eutectic salts, salt hydrates, and paraffin have all been tried. Paraffin is one of the few substances that undergo solid to liquid phase change at 38°C (100°F) which is in the temperature range needed. It is not recommended that latent heat storage be used at present. The salt hydrates are subject to settling out, which limits rehydration; they work at first but ultimately have to be replaced with new materials.

The optimum storage temperature depends upon what use is to be made of the system. If it is to be used for space heating then its temperature should be in the range of 40 to 45°C (113 to 131°F). If it is to be used for direct cooling then it must be somewhere around 5 to 15°C (41 to 59°F). This low temperature can be obtained by operating the collectors at night when the outside air is colder. If the system is to be used for absorption air conditioning, then the heat transfer fluid must be quite hot, 110 to 120°C (230 to 248°F).

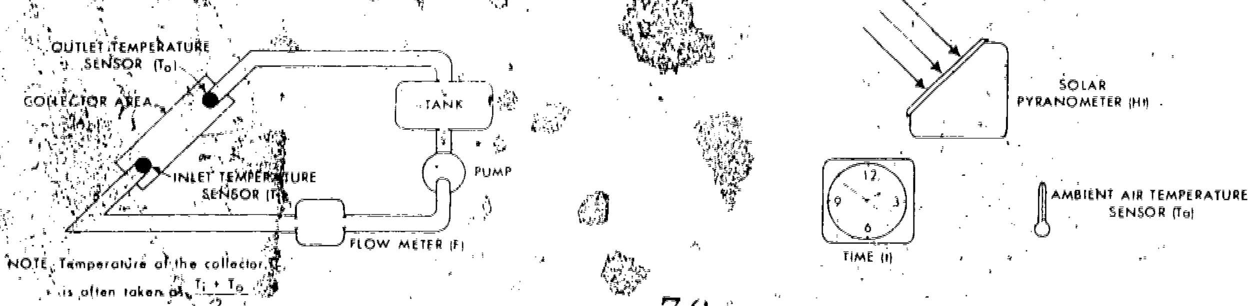
Circulation and storage of the heat transfer medium require the use of pipes, ducts, pumps and fans, and associated control equipment. Heat exchangers may be necessary, to interface a solar collector using water as a heat transfer medium with an existing hot air system.

SPACE HEATING - ACTIVE SOLAR SYSTEM

Flat Plate Collector Efficiency

Procedures have been developed by NBS and ASHRAE and adopted by HUD to compare collector efficiencies. Test facilities, such as the Desert Sunshine Exposure Test Facility in New Mexico, have been set up to calculate collector efficiency following these procedures. Most major collector manufacturers can provide these independent test results to prospective buyers. The basis of most of these efficiency tests is the determination of collector efficiency as a function of both the solar radiation intensity and the difference between the ambient outside air temperature and the collector absorber temperature. Collector efficiency is defined as the ratio between the energy collected (absorbed by the fluid) and the energy incident upon the collector.

In order to determine these quantities, the collector is set up outdoors, properly oriented, and connected to the inlet; temperature sensors are attached to the inlet and outlet of the collector. Tests are conducted around noontime over a three week period.



76

Data obtained includes: flow rate of fluid (F), inlet temperature of fluid (T_i), outlet temperature of fluid (T_o), ambient air temperature (T_a), solar pyranometer reading (H_r) in BTU/ft^2 hr or Kjoules/m^2 hr, time (t) in hrs.

$$\% \text{ Collector efficiency, } n = \frac{\text{Heat collected by fluid}}{\text{Solar energy incident on collector}} \times 100$$

The heat collected by the liquid is stored as sensible heat; we have already seen that this depends on mass, specific heat, and temperature change. Therefore, we use the following equation:

Heat collected by liquid (Q) = weight of liquid (w) x specific heat of liquid (Cp) x temperature change of liquid (ΔT).

$$Q_{(BTU)} = W_{(pounds)} \times Cp_{(BTU/pounds\ ^oF)} \times \Delta T_{(F^o)}$$

The weight of the liquid passing through the system depends on the rate of flow and the time.

Weight of liquid = Rate of flow x Time

$$W_{(pounds)} = F_{(pounds/hour)} \times t_{(hour)}$$

OR

$$Kg = \frac{Kg^o}{hour} \times hour$$

ΔT is the difference between the temperature of the liquid at the inlet and outlet of the collector, $\Delta T = (T_o - T_i)$ in ^oF or ^oC.

The heat collected therefore is:

$$Q = F \times t \times Cp \times (T_o - T_i) \quad \text{BTU's or Kjoules}$$

Now in order to find the efficiency, Q must be divided by the incident solar energy on the collector. The value of the incident energy, I, is found by the following equation:

Incident energy (I) = Collector area (Ac) x time x pyranometer reading (Hr)

$$I_{(BTU)} = Ac_{(ft^2)} \times t_{(hr)} \times Hr_{(BTU/ft^2\ hr)}$$

OR

$$Kj = m^2 \times hr \times \frac{Kj}{m^2} \times hr$$

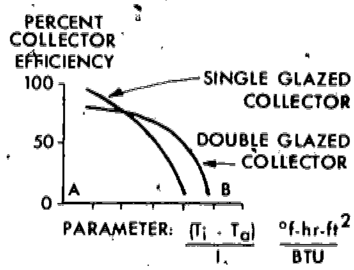
Therefore the % efficiency (n) = $\frac{F \times t \times Cp \times (T_o - T_i)}{Ac \times t \times Hr} \times 100.$

In these tests, the efficiency is plotted agains a parameter defined in HUD specifications (ASHRAE and NBS differ slightly) as:

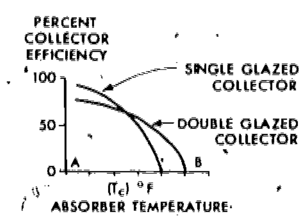
$$\frac{\text{Inlet temperature minus ambient outside air temperature}}{\text{Solar energy incident on collector}}$$

$$\frac{T_i - T_a}{I} \qquad \frac{{}^oF\ hr\ ft^2}{BTU} \qquad \text{OR} \qquad \frac{{}^oC\ hr\ m^2}{Kj}$$

The graph plotted, then, is collector efficiency vs. the parameter, $\frac{(T_i - T_a)}{I}$

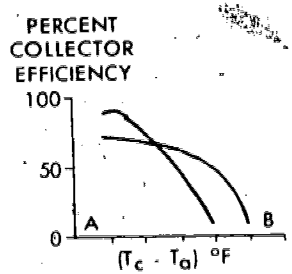


It is not as easy to picture the significance of this plot as it is some of the other efficiency curves used. Instead of plotting % Efficiency vs. $\frac{(T_i - T_a)}{I}$, another method plots % Efficiency vs. Absorber Temperature; absorber temperature is usually taken as the average of the inlet and outlet temperatures: $\frac{T_o + T_i}{2}$.



One can readily see now that at high absorber temperatures there is a marked increase in efficiency with double glazing. However, if you are interested in operating the collector at low absorber temperatures, then single glazing will actually provide greater efficiency than double glazing.

A third way of plotting efficiency curves plots collector efficiency vs. the temperature difference, $(T_c - T_a)$. The curves immediately above (% efficiency vs. absorber temperature) had to have been obtained at some ambient air temperature. Therefore, this should have been taken into consideration since heat losses and efficiency depends on the ambient air temperature. This new way of plotting efficiency takes this into account and makes the curves more useful. You can



see the greatest efficiencies occur when the difference between the collector temperature and the ambient air temperature is small. Remember the collector temperature depends to a large extent on the rate of flow of the fluid through the collector; a fast flow rate produces a lower collector temperature and therefore a smaller $(T_c - T_a)$. This means the efficiency will be higher. You do not want conditions near stagnation to occur because, not only do you run the risk of damaging the system by overheating it, but you also have greatly reduced efficiency.

You should examine each of the parameters involved in the determination of the efficiency and learn how it affects the overall operation of the system. Careful adjustment of each (if possible) will result in maximum energy collection and storage.

NOTE: The above discussion refers to a collector using a liquid heat transfer agent. Slight modification of the equations may be necessary, depending on the particular units in which your equipment is calibrated. For example, perhaps your flow meter reads in gallons/minute (or perhaps you have no meter and you measure the flow by allowing the water to fill a bucket or pail). You then need to use appropriate conversion factors to change your value of gallons/minute to pounds/hour so you can use it in the equation.

If you wish to apply this equation to a system using air instead of a liquid, then the equation must be modified. If you do not know the pounds/hr of air flowing through the system, but do know the velocity of the air through the ports, then the efficiency can be found by :

$$\% \text{ Collector efficiency} = \frac{(\text{density} \times \text{velocity} \times \text{T} \times \text{radius of port}^2 \times \text{time}) \times Cp \times \Delta T}{Ac \times t \times H_T}$$

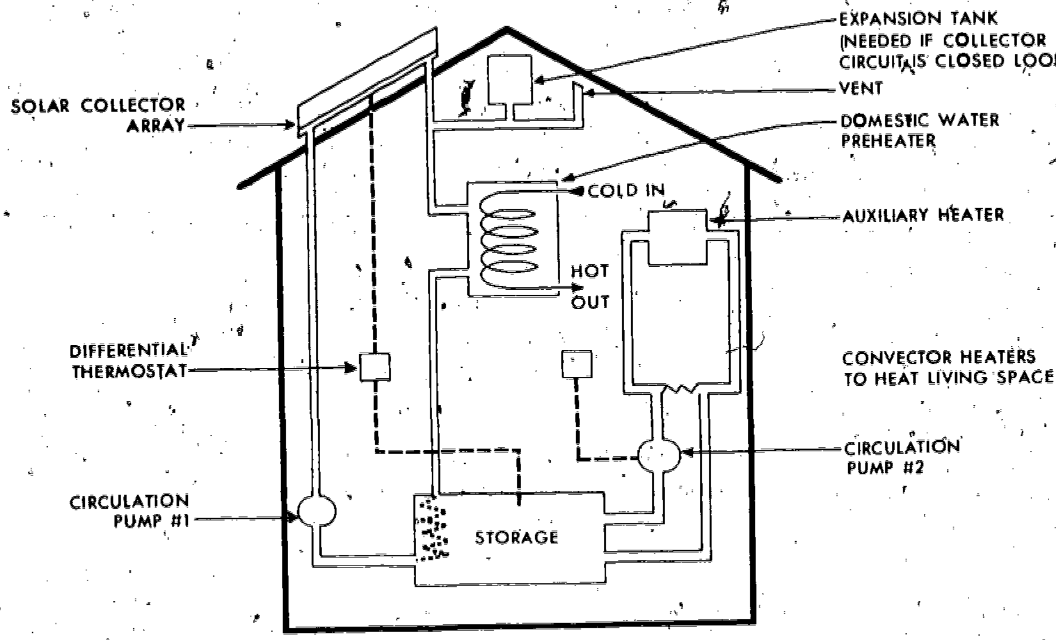
$$\% \text{ Collector efficiency} = \frac{d \times v \times \pi r^2 \times t \times Cp \times \Delta T}{Ac \times t \times H_T} \times 100$$

Notice that time in the numerator and denominator will cancel out; however, it was left here so that you can see that the numerator represents the absorbed energy and the denominator the incident solar energy. The problem in using these equations is to make certain that units are consistent. You can not use seconds in one place and hours in another; likewise you can't mix metric and English units. Be sure to convert your pyranometer reading to units consistent with the rest of the equation.

SPACE HEATING - ACTIVE SOLAR SYSTEM

Its Operation

We have discussed each of the components of an active solar heating system. Here we shall discuss the operation of an entire system, such as the liquid system shown below.

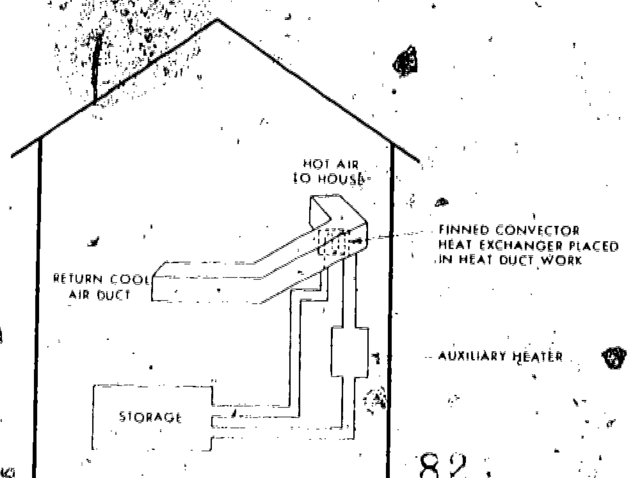


XV-1

The solar collectors are mounted on a south facing roof. They are placed at an angle of inclination, measured with the horizontal, of roughly 10^{o} plus local latitude. This may vary; maximum efficiency would be obtained if the collector plane were always at right angles to the sun's rays. A misalignment of much as 35^{o} results in a reduction of incident radiation of only 10 percent.

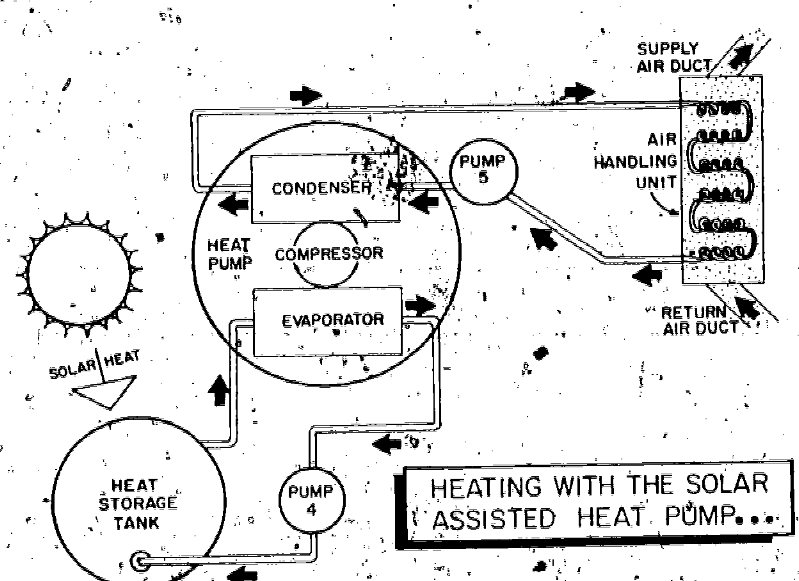
The differential controller is a device that senses the temperature on the collector absorber plate and in the storage tank. When the collector temperature is a few degrees warmer than the liquid in the tank, the controller turns on circulating pump #1, and the system stores heat in the large tank. (The controller might also activate various off-on valves that have not been shown in the diagram.) Toward the end of the day as the sun's rays diminish, the tank temperature becomes higher than the absorber plate; the differential controller shuts off the water flow through the collector and the water drains out of the collector back into the storage tank. The expansion tank shown in the drawing is needed in case the collector circuit is a closed loop, using a heat exchanger to interface with the storage tank. When the living space thermostat senses "heat" is needed, it turns on circulating pump #2; heat is now transferred from the storage tank to the interior of the house by means of the convectors. In the event the temperature of the tank drops below that called for by the thermostat, the auxiliary heater (gas, oil, electricity) is turned on. By proper use of control devices and valves (not shown) this auxiliary heater could be used to either circulate its own heated water through the convectors alone or it could add heat to the storage unit. A heat exchanger is also shown that acts as a preheater for the domestic hot water system.

A liquid system can easily be connected to (interfaced with) an existing forced hot air system as shown below:



Liquid collector systems interface very easily and efficiently with forced air systems. The water temperature needed to space heat using hot water convectors, as in Figure 1, is 70^0 to 85^0 (160 to 180^0F); in the case of forced hot air (Figure 2) the air temperature needs to be only 27^0 to 38^0C (80 to 100^0F). Hot-air collector systems also interface easily with forced air systems, but the control and pumping (blowing) of air is more complicated and expensive than that of water.

The solar-assisted heat pump may be a good choice for a heat system in much of the country. Figure 3 shows how the evaporator of the heat pump is coupled to the heat storage tank of the solar collector system. The coefficient of performance (C.O.P.) of a heat pump ($\frac{\text{energy to living space}}{\text{energy input to compressor}}$) depends on the temperature at which the evaporator coils operate. 1) This is normally the outside air temperature. 2) The efficiency of a heat pump decreases with decreasing outside air temperature. 3) At 0^0F the C.O.P. is only about 1.4, at 30^0F it is about 3, and at 50^0F the C.O.P. is about 4. During very cold weather, considerable savings can be realized by operating the evaporator coils at the intermediate temperature of the heat storage tank, even though this temperature may still be low compared to that actually needed to heat the interior of the house. Furthermore, the heat pump can be reversed in summer to cool the interior of the house.



XV-3

ELECTRICAL PRODUCTION - SOLAR CELLS

Direct conversion of light energy into electrical energy is possible by means of a device called the solar cell, or photovoltaic cell. Nearly everyone has heard of these devices because of their widely acclaimed use aboard space vehicles. They are solid-state devices closely related to the transistor. As such, they are made of a class of materials known as semi-conductors. These materials have electrical resistances higher than those of the really good metallic conductors such as gold or copper, but considerably lower than those of the poor conductors (insulators) such as glass or mica.

Most solar cells are now made of single crystals of silicon, although a large number of compounds such as gallium arsenide, cadmium sulfide, and cadmium telluride are being investigated. Selenium cells have been used for many years, but these have much lower efficiencies than silicon cells.

Silicon atoms are similar to carbon atoms in that they have four valence electrons that they share, if possible, with other atoms in covalent bonds. This covalent bonding, in which two silicon atoms share a pair of electrons in their outermost shells, is the most stable configuration for silicon atoms. Silicon atoms therefore, normally arrange themselves in a cubic crystal lattice in which each atom forms four covalent bonds with its neighbors.

```
   !     !     !
---Si-----Si-----Si---
   !     !     !
   !     !     !
---Si-----Si-----Si---
   !     !     !
   !     !     !
---Si-----Si-----Si---      -----
   !     !     !          (indicates covalent
                           bond consisting of
                           two shared electrons)
```

Since all the valence electrons are held fairly tightly in such an arrangement, pure silicon is a rather poor electrical conductor. Conduction depends on electrons that are relatively free to move around through the crystal or metallic structure. By adding a small amount of impurity to the silicon (roughly 1 part per million) this condition can be altered significantly. For instance, if atoms are added that have five valence electrons (arsenic, phosphorous, antimony) there will be an excess of non-shared valence electrons; these will be relatively free to move around through the crystal. Silicon with such donor type impurities is called N-type silicon, because the excess electrons act as negative charges.

```
   |      |      |
---Si-----Si-----Si---
   |      |      |
   |      |      |
---Si----●As-----Si---
   |      |      |
   |      |      |      (indicates unshared
---Si-----Si-----Si---   valence electron)
   |      |      |
```

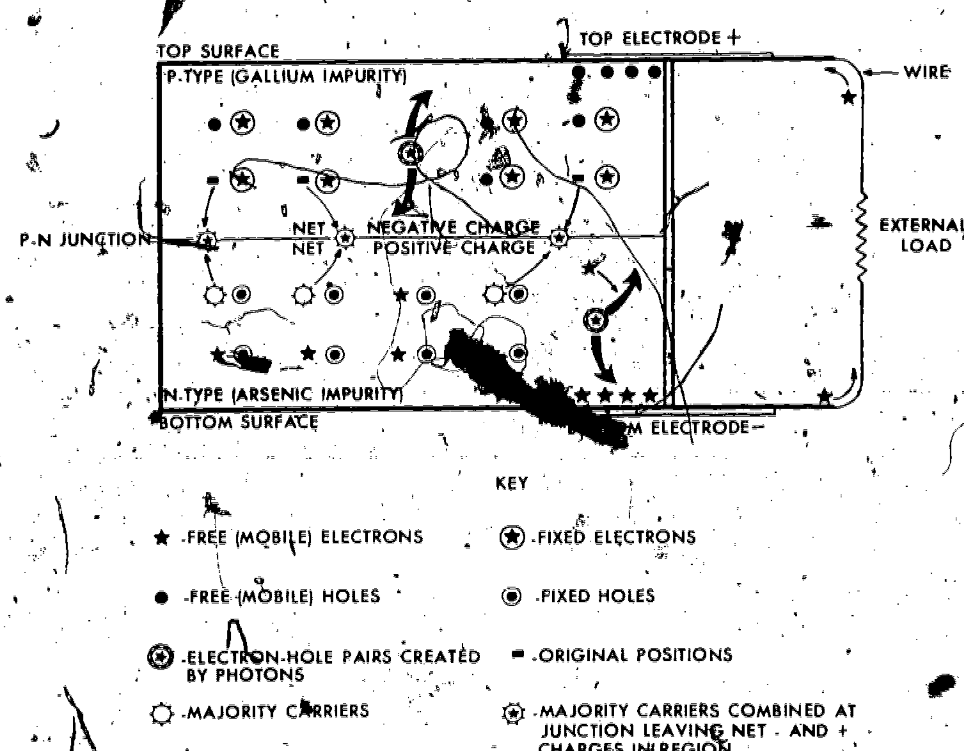
On the other hand, if impurities, such as boron, gallium, or indium having only three valence electrons are added, there will be a deficiency of valence electrons. If these acceptor impurities steal valence electrons from nearby silicon atoms in order to complete their covalent bonds, holes will be left in neighboring electron pair bonds. The holes represent a deficiency of electrons and therefore act as positive charges.

```
   |      |      |
---Si-----Si-----Si---
   |      |      |                 ⊗
   |      |      |
---Si-----Ga-----Si---      (indicates hole formed
   |      |   ⊗               when electron moved over
   |      |      |            to complete gallium's
---Si-----Si-----Si---        bonds)
   |      |      |
```

This type of material is called P-type silicon. The holes move around through the crystal as atoms compete for electrons to complete their electron pair bonds. It should be noted that the acceptor atoms (like gallium) in taking on an extra electron become negatively charged just as the donor atoms (like arsenic) become positively charged as they lose their fifth electrons in the N-type silicon. (There are also minority carriers: holes in N-type silicon or electrons in P-type silicon. These arise from normal breaking of bonds due to thermal agitation; absorption of light energy, etc.)

The solar cell itself consists of a N-type silicon base with an extremely thin P-type silicon surface. The sunlight can actually pass through this thin surface and penetrate beneath the P-N junction. Conduction leads are attached to the upper and lower surfaces of the crystal.

SILICON SOLAR CELL



Consider the previous diagram. The interface between the P-type and N-type silicon is known as the P-N junction. When the two layers are first formed, they are electrically neutral. When placed in contact with each other, diffusion of the majority carrier occurs; the holes in the P-type silicon and the free electrons in the N-type silicon move toward the junction where some of them combine and become fixed. The removal of some of the electrons from the N-type material near the P-N junction leaves a net positive charge in this region and the removal of some of the holes from the P-type material leaves this with a net negative charge. This constitutes an electrical potential or barrier electric field across the P-N junction. The build up of this field prevents the rest of the majority carriers from crossing the junction and combining; this limits the junction potential (voltage) to about 1/2 volt.

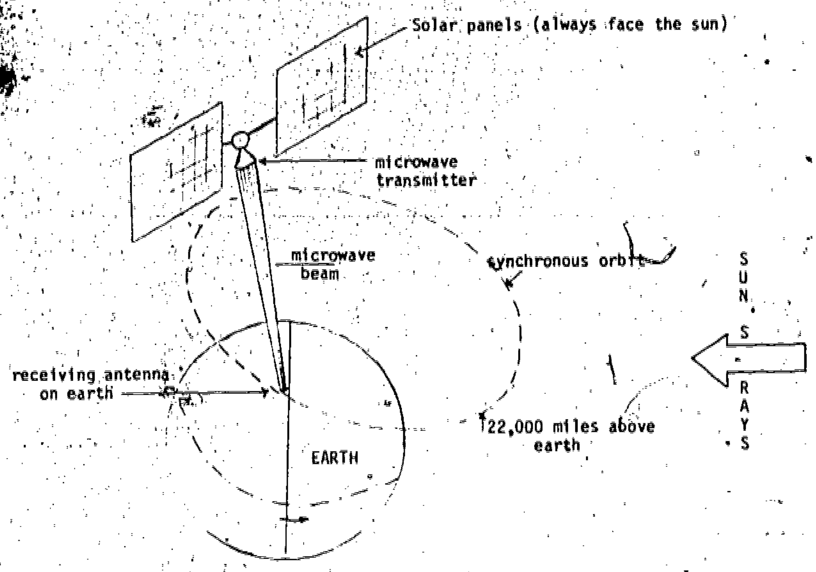
The surface of the solar cell is now exposed to sunlight. Photons (the little bundles of energy that make up light) collide with the valence electrons of the atoms of silicon on both sides of the P-N junction. If the photons have sufficient energy, they knock the valence electrons loose and they can act as conducting electrons. In order for an electron to be knocked loose from an atom, it has to absorb a certain amount of energy. The amount of energy that a photon has, depends on the frequency, or wavelength, of the light. E = hf where E stands for energy in appropriate units, h for a constant (Planck's constant), and f for frequency. The higher the frequency (or the shorter the wavelength) the greater the amount of energy carried per photon. There is a certain minimum threshold frequency of light below which photons will not knock electrons out of a particular metallic element. In the case of silicon, all visible light and even some infrared light (to a wavelength of about 11,500 Å) can knock electrons loose from their bonds so they may become conducting electrons.

When a free electron is produced, so is a corresponding hole which can act effectively as a mobile positive charge. As the electron-hole pairs are created by the photons striking the electrons within the solar cell, the electrons and the holes move under the influence of the barrier field toward opposite faces of the cell. The free electrons are repelled by the net negative charge of the P-type region, toward the N-type region or bottom section of the cell; the holes are driven by the net positive charge toward the top of P-type region. Of course not all holes or electrons arrive at the top and bottom surfaces of the cell where the electrodes are attached; recombination of holes and electrons occur throughout both regions of the cyrstal. However, the displacement or separation of the free charges, (electrons) toward the lower electrode and holes toward the upper electrode, establishes a potential difference (voltage) between the two surfaces. If an external load is connected to the two electrodes, electrons will travel from the bottom electrode (N-type region) through the wire and load to the top electrode and P-type region where they combine with the holes.

In addition to providing electrical energy for space vehicles, solar cells have been used as low energy sources in very remote land areas, as battery chargers, aboard boats and navigation buoys, and in communication systems. However, their widespread use has been limited by their cost. Silicon itself is inexpensive. But it must be highly purified for use in solar cells and it must be grown slowly in small quantities into single crystals. The crystals are carefully sliced with diamond saws into thin wafers a few hundredths of an inch thick. Carefully controlled amounts of impurities must be introduced into the crystal to form the N and P layers of the cell. The typical cell produces a current (maximum) of about 30 milliamperes/ square centimeter and a maximum voltage of about 1/2 volt. Maximum power output is about 15 milliwatts/square centimeter. Solar cells can, of course, be arranged in parallel or series to provide higher voltage and current outputs. Efficiency of production-run cells is about 11 percent; maximum efficiency appears to be somewhere around [illegible] percent. In 1960 the cost of solar cells was approximately $175,000 per kilowatt. In 1975 the cost was still $30,000 per kilowatt. The largest terrestial solar cell unit built in this country to date is a one kilowatt unit consisting of about 14,000 individual cells (Mitre Corporation near Washington, D.C.). It is estimated that the cost of solar cells must be reduced to about $200 per kilowatt in order to become competitive for use in central power station generation. The use of centralized solar cell power generation also requires large tracts of land. It would require roughly 30 acres of land to produce about 10 percent of our projected electrical energy needs for the year 2020.

There are two possible ways to use solar cells without tying up vast quantities of land. One involves the decentralization of electrical generating facilities. In such a system, much of an individual home's electrical needs would be provided by means of a roof-mounted solar panel array. At present, a 200 foot by 30 foot panel of solar cells can produce over 1 kilowatt of power, averaged over the entire year, with a maximum of about 5 kilowatts of power at noon on a sunny day. This is more than adequate to meet the electrical needs of the average household. The initial cost is prohibitive however; and in addition, large scale electrical storage facilities are needed. At night, when the electrical energy is most needed, the sun is not shining on the solar cells. Electrical storage, like the solar cells themselves, is not cheap.

The other suggested way to use solar cells without tying up large amounts of land is way out -- roughly 22,000 miles from the earth. It has been suggested that two geosynchronous power plants be constructed in space where the amount of solar energy received is as much as 15 times greater than that received by the same panels mounted in a fixed position on earth. Here in space the solar radiation is greater, there are no clouds, the panel can always be positioned at right angles to the sun's rays, and the sun shines twenty-four hours a day.

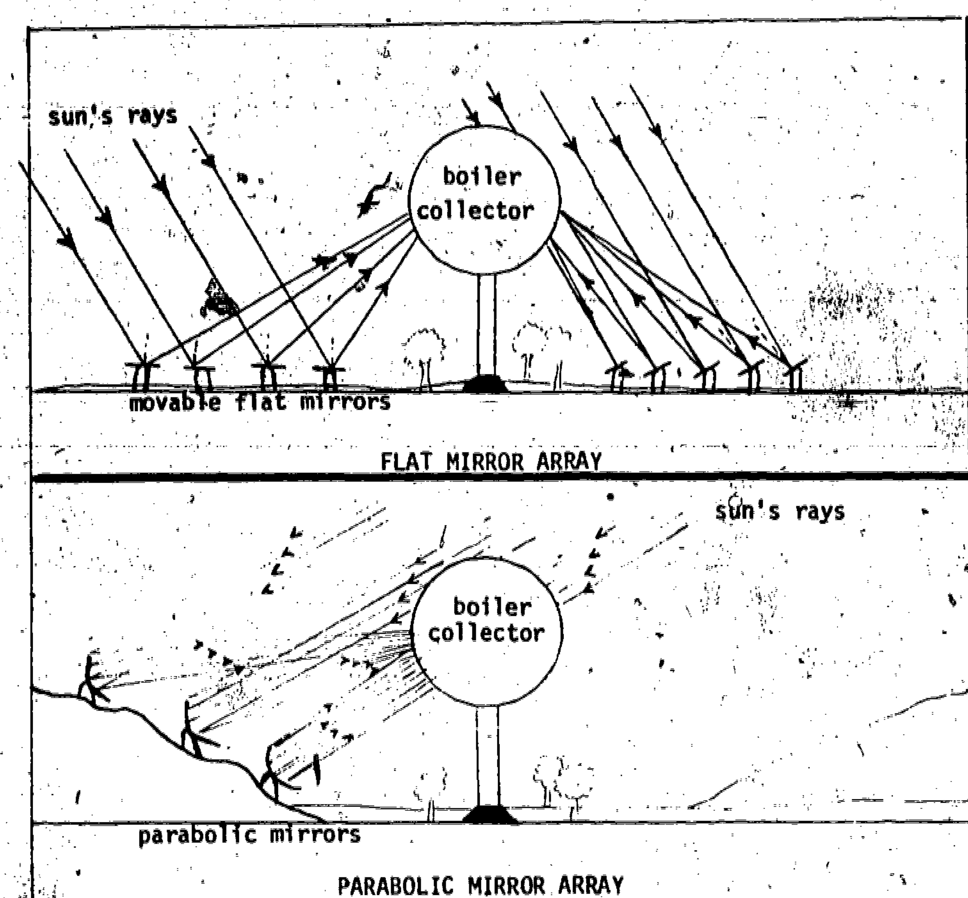


Two wing-like solar panels nearly 3 miles in length and width would generate electricity. This would be converted to energy in the form of microwaves and beamed down to earth by a transmitting antenna 1/2 mile in diameter. On earth a receiving antenna about 4 miles in diameter would collect the energy and convert it back into electricity with an overall efficiency of about 60 percent. Such a unit would produce about 5,000 megawatts. By today's standards, a 1,000 megawatt power plant is considered large. Needless to say, this is not likely to be built within the immediate future.

ELECTRICAL PRODUCTION - THE POWER TOWER

In the previous section we examined the direct conversion of light energy into electrical energy by means of the solar cell. Its many advantages were offset by its current prohibitively high cost. There are other ways of producing electricity from the sun's energy. One involves converting the sun's radiant energy into thermal energy and then into electrical energy by means of a boiler, steam turbine, and electric generator combination. The high temperature needed to produce very hot steam is obtained by concentrating the sun's energy on a centrally-located, elevated boiler (power tower) through the use of many focusing mirrors. The advantages of such a system are its relatively high efficiency and its advanced state of technology. A large electric generator is one of our most efficient machines, nearly 99 percent efficient; a large steam turbine has an overall efficiency of about 40 percent. The high temperature of the steam produced by the power tower (900°F to 1,000°F) is comparable to that produced by conventional fossil fuel plants. Focusing-type collectors are inherently more efficient than low temperature flat plate collectors; the efficiency of collection and absorption of energy by the boiler could be as high as 90 percent. The overall efficiency of the power tower or central receiving system would be over 35 percent.

There are basically two types of focusing reflector systems. One makes use of movable flat mirrors arranged so that they act as a large single parabolic surface with the tower at the focus. The second system uses large individual parabolic mirrors that are also movable. These concentrate the sunlight on the surface of the tower. In either case, much of the overall cost of the system is in the control and moving of the mirrors.



There are actually two types of high temperature collectors. One type absorbs energy over the whole surface of the boiler. This boiler may be enclosed within an evacuated glass sphere. The other type works somewhat like a "black body" where the concentrated beams of radiant energy are directed into a cavity on the side of the spherical collector. Coils inside the sphere are heated by the absorbed energy, and the water inside the coils is changed to high temperature steam. This type of collector is more efficient; however, it requires more sharply focused beams and a greater precision in tracking.

A number of power tower units have been proposed. One would consist of a 150 foot diameter boiler mounted atop a 1,500 foot high tower. Over a thousand flat mirrors about 10 feet across would focus the sun's rays on an area on the boiler's surface. The mirrors would be positioned on about one square mile of land surface surrounding the boiler. The output of the system would be about 100 megawatts. At the present time a smaller, 5 megawatt power tower is being built for evaluation and testing near Albuquerque, New Mexico. Most engineering studies have indicated that these units should be competitive with standard fossil fuel plants. In particular, they may be valuable for supplying power during peak load demand. Should this occur during the daytime, it would minimize the problem of energy storage for periods when the sun is not shining. In general, these power plants would have to be located in areas that are relatively free of clouds since focusing collectors can utilize only direct radiant energy; diffuse radiation is of no value.

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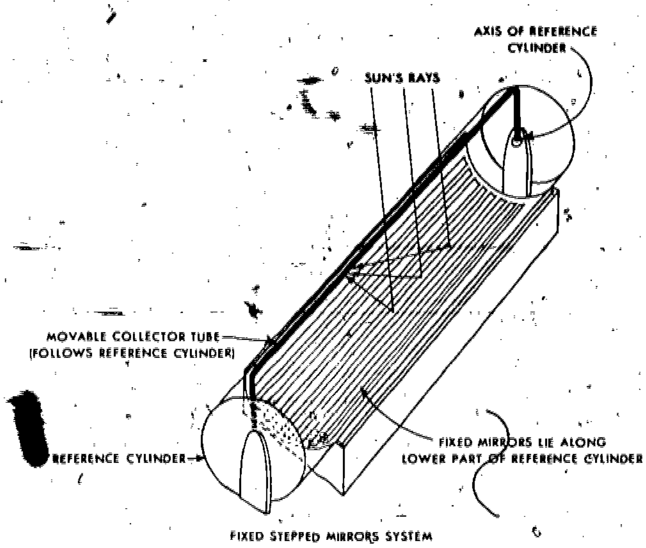
ELECTRICAL PRODUCTION - THE DISTRIBUTED SYSTEM

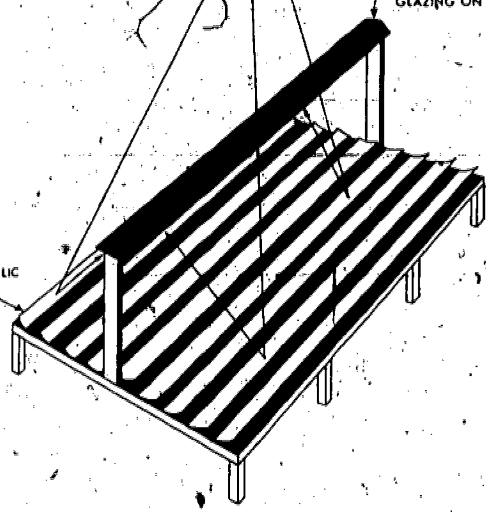
The power tower discussed in the previous section makes use of many mirrors to focus the sun's radiant energy on a single centrally located boiler. The alternative to this is the distributed system; this system makes use of many mirrors to concentrate the sun's energy on a series of pipes containing the heat transfer medium, which might be water, liquid metal, air, or some other fluid. The distributed system can use diffuse light to some extent; however, since heat transfer takes place at the remote collectors instead of at the boiler, and since the temperature in most cases is considerably lower (200 - 500°F), (90 - 260°C) the efficiency is less. However, in a few of these systems, the use of tracking parabolic mirrors can result in temperatures over 800°F (427°C).

A large number of distributed collector designs are undergoing development and testing under funding of the United States Department of Energy. Some of these are shown in the sketches below:



In the full scale model this unit would be about 10 m wide, 180 m long, and 16 m high.

Another system being studied makes use of segmented mirrors that approximate a cylindrical parabola. The mirrors track the sun and concentrate its energy on a fixed collector tube mounted in a miniature flat plate collector assembly:



SEGMENTED MIRROR SYSTEM

In this particular system, the collector tube is a heat pipe surrounded by a glass evacuated cylinder. A heat pipe is an especially efficient heat transfer device that carries energy from the hot end to the cool end of the pipe. An enclosed liquid evaporates at the hot end of the pipe, condenses at the cool end, and is returned to the hot end by a wick. Since this pipe is a closed system, a heat exchanger is needed to transfer energy from the pipe to the operating fluid. Of course, an ordinary collector tube carrying water or some other liquid could be used in this system instead of a heat pipe.

If these distributed systems are ultimately used to generate electricity, then the heated fluid must be pumped to the generating station, where the heat will be used to change a liquid such as water into steam in order to drive a turbine generator set. One of the disadvantages of a distributed system is the lower temperature of the heated fluid; it may be necessary to develop turbines that operate on materials other than steam, since modern steam turbines are designed to operate efficiently only at temperatures approaching 800 - 1,000°F (472 - 600°C).

These systems could be used for purposes other than producing electricity, such as space heating or hot water production. They share with the power tower system the disadvantage of requiring large heat storage facilities (and reduced efficiency) if they are to be used at times other than when the sun is shining.

SECTION XIX

BIOMASS CONVERSION

In section X, "The Uses of Solar Energy", we mentioned that one of the energy conversion processes by which the sun's radiation can be utilized is photochemical in nature, i.e., photosynthesis. In fact, photosynthesis is the only practical photochemical process by which solar energy can be converted into stored chemical energy. The complex process of converting carbon dioxide and water in the presence of chlorophyll and solar energy to carbohydrates (stored energy) and oxygen is still not completely understood; it has never been totally duplicated in the lab. Therefore, if man wishes to utilize the sun's energy through direct photochemical conversion, he must turn to plants.

The term biomass refers to all organisms, living or dead, that cover the earth; as such it includes all plants and animals, and their waste products. Biomass is measured in units of mass or volume per unit area. As a potential source of energy, biomass is often defined as growing plant material, or using organic wastes, including human and animal wastes such as garbage, manure, crop residue and sawdust, for fuel. Biomass conversion is the process of obtaining useful energy from biomass. Our bodies do this when we eat foods; the energy stored in the food is used to supply our bodies with the energy needed to carry out body functions. This, of course, is not the biomass conversion process we intend to discuss here; rather, we will examine some ways in which biomass may be converted into useful fuels, or used directly as an alternative to the dwindling supplies of fossil fuel.

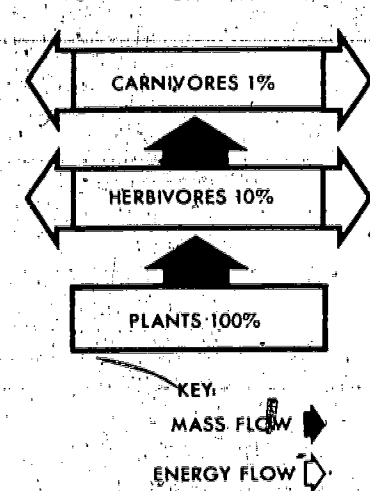
We will start by looking at the photosynthesis process from the standpoint of solar energy conversion. The other conversion processes we have been looking at use the sun's energy directly; here we are faced with at least one intermediary step: solar energy photosynthesis, stored chemical energy burning useful heat energy. Additional steps might be required if the biomass were not burned directly, but instead converted first to a higher quality fuel. Each time additional conversion steps are added, efficiency decreases.

In an earlier section we saw that the amount of solar energy arriving at the edge of our atmosphere was approximately 1.94 cal/cm^2/min, but by the time this was averaged over the whole earth's surface and depletion had occurred as the solar beam passed through the atmosphere, the amount of available energy was reduced to an average of about .25 cal/cm^2/min. However, at any one spot, the maximum insolation might be as much as 1.4 cal/cm^2/min at solar noon on a bright, clear day. We also noted that on an average, roughly 47 percent of the original solar beam was absorbed by the earth. This is not, however, the amount of energy available to the plants; most of this is either reflected or reradiated, removed by conduction or convection, or stored as latent heat in the evaporation of water. Energy conversion is then further reduced 50 percent because only wavelengths in the visible region of the spectrum are effective in the photosynthesis process. About one-half of the incident radiation at the surface is in the visible spectrum. Altogether, about 1 percent of the sunlight falling upon the surface of the earth is used by plants in the photosynthesis process.

Laboratory investigation has shown that the upper limit of conversion efficiency for photosynthesis (solar energy ⟶ plant chemical energy) is about 30 percent. However, plants seldom find ideal conditions; the temperature may be so low that only minimum conversion occurs, water supplies may be limited, or other essential nutrients may be lacking. Therefore, even though the plant may be receiving sufficient sunlight, little conversion to biomass occurs. In addition, much of the energy absorbed by the plant is used in respiration and maintenance rather than biomass production. The end result is that photosynthesis efficiencies range from .3 to 3 percent, with an average around 1 percent.

All in all, somewhat less than 1/10 of one percent (0.1%) of the total energy arriving at the earth's surface is converted by plants into stored chemical energy through the process of photosynthesis. If this biomass moves up through food chains, about 90 percent of the available energy is lost at each step or exchange between organisms. (See figure 1).

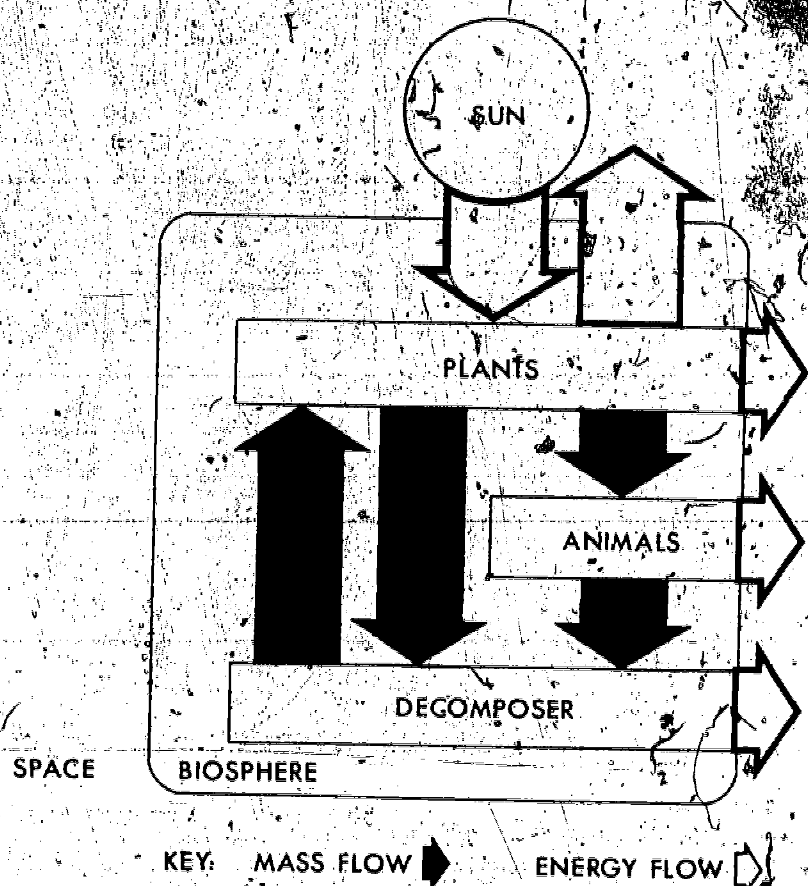
ENERGY LOSSES IN FOOD CHAINS
Percent of Original Energy of Plants Remaining After Exchange



XIX-1

It is important to remember, also, that while all matter is returned ultimately to the biosphere and recycled, energy must be continuously supplied, since it flows through the system only once, ending up eventually as heat energy lost in space. (See figure 2).

BIOMASS ENERGY FLOW



XIX-2

By now you should recognize the fact that the process of converting solar energy into biomass is extremely inefficient. Inefficient as it may be, it is the only source of our food supply. Furthermore it does offer us one more avenue by which we can obtain energy from the sun.

Let us look now at some of the ways that this energy can be obtained. We said earlier that biomass is often placed in one of two categories from the standpoint of energy conversion: the growing of plant material or the using of organic wastes.

Plant material, of course, is used for food, as well as for energy production. Whether existing crop land should be removed from food production in order to use it for energy production is a difficult question. Many people believe that existing crop land is already needed for food, not energy. But American agriculture, as presently practiced, places great reliance on outside energy supplies, such as chemical fertilizers and mechanized labor, for crop production, and hence is extremely inefficient when these outside energy sources are taken into account. In terms of energy, natural grasslands are far more efficient than intensively farmed land. It has been suggested that more energy efficient crops than those presently used can be found. For example, photosynthetic efficiencies of 20 to 30 percent (of gross productivity including both biomass conversion and heat of respiration) have been obtained in the laboratory using the alga Chlorella. This is roughly ten times the efficiency of corn production (1.6%) rice (2.2%) or pasture land (1%).

Certain land plants produce high yield biomass, and as a result have been suggested for either food or energy production. These include sunflower, comfrey, kemat, sudan grass, and napier grass. Fast growing trees, such as poplar, ash, and sycamore, could be used for energy production. These trees could be grown as brush and cut every two to three years.

The tremendous quantities of organic waste produced each year in the United States could also be converted into energy. This would include such materials as manure (200 million tons), crop and food wastes, (390 million tons), logging and wood manufacture (55 million tons), garbage (100 million tons), and sewage (12 million tons). (These are 1971 figures for dry weight quantities). Of course, not all of this material is readily collectable. It is estimated that the readily collectable wastes could furnish about three precent of our energy needs. It is also argued that crop and food wastes could better be used by returning them to the land as fertilizers and soil conditioners, rather than in energy production, since they have such a low overall biomass conversion efficiency anyway.

The actual chemical processes used to obtain energy from this organic waste biomass can be divided into thermal, or heat requiring processes, and biological processes. Heat demanding processes include direct burning, pyrolysis, hydrogenation, hydrogasification, and acid hydrolysis; biological processes include composting, anaerobic digestion, and fermentation. These are summarized below:

<u>Direct burning</u>: This is probably the most straightforward and cheapest way to recover energy from biomass. Efficiency, in terms of heat recovery, is between 60 and 80 percent. This could be used to supplement or replace fossil fuel use in the home. Municipal garbage and trash could be used as a supplementary fuel at power plants.

<u>Pyrolysis</u>: This is a process in which organic wastes are heated to high temperatures (400 - 900^oC) in the absence of air to cause a decomposition into several combustible products: char, oil, and gas. Some studies have shown a net loss in energy in the process; more energy is expended than can be obtained from the products. Destructive distillation is pyrolysis applied to wood or wood refuse; distillation is used to recover methyl alcohol (wood alcohol).

<u>Hydrogenation</u>: In this process hydrogen is added to carbon molecules in the substance by heating in the presence of a catalyst. Often the process uses carbon monoxide and steam at very high pressure (2,000 - 6,000 psi). Low sulfur oil can be obtained in this way.

Hydrogasification: Organic wastes such as manure can be reacted directly with hydrogen gas at high temperature (500 - 600°C) and pressure (1,000 psi) to produce methane and ethane gas.

Acid Hydrolysis: Wood wastes can be treated with heat and acid to convert them into sugar. The sugar is then fermented and distilled to produce ethyl alcohol (grain alcohol).

Fermentation: Organic wastes are decomposed in the absence of air by the action of yeast. Ethyl alcohol, a fuel, is produced.

Anaerobic digestion: This is the bacterial digestion of organic wastes in the absence of air to produce methane gas.

Composting: Bacterial digestion of organic wastes (in practice, plant wastes and manure, only) in the presence of oxygen produces soil enriching and conditioning substances (compost).

As seen, organic wastes (biomass) can be converted into useful energy by a number of different processes. Direct burning of wood is perhaps the most efficient of these; for example, it produces roughly five times the energy produced by burning ethyl alcohol made from the same quantity of wood. Growing, collection, and conversion of biomass require large sums of energy in most cases. Often a net energy saving could be realized just by the elimination of waste and the recycling of the materials, rather than by their conversion into energy.

SOLAR HEATING - ECONOMIC AND LEGAL CONSIDERATIONS, AND MORE

Solar heating has not yet come of age, but it's growing up fast. Within the past few years several thousand solar heated homes have been built. Increasing amounts of state and federal monies are being directed toward solar energy research. New and existing companies are rapidly entering the solar field, and the solar products market is in a state of flux and development.

However, it is difficult to assess what role solar energy will play in the immediate future. Costs for other energy sources are rapidly increasing as supplies are being depleted. Unfortunately, much of the general public still perceives the energy crisis as the cries of alarmists, or as a conspiracy of the large oil companies, or at least as a plot of the environmentalists.

Legislation concerning solar energy and "sun rights" is also in a state of flux. At the present time there are no solar access rights laws in force in this country, although a few states have recently adopted legislation that in some ways establishes solar rights. Several states have passed legislation for state financing of solar energy research and development. A few states and many communities now have solar heating references in building codes.

Many states are actively encouraging solar energy use, most notably in the area of tax incentive. According to the National Environmental Systems Contractors Association, these states now offer solar tax incentives:

Arizona: permits deducting the cost of solar devices from state income taxes, amortized over 36 months.

California: formerly allowed a 10 percent credit, up to $1,000 against personal income taxes. Under a new law, residents of single-family dwellings now will be entitled to take either a 55 percent income tax credit or $3,000, whichever is the lesser, for sums they spend on solar energy equipment for heating, cooling, ventilation, or to provide hot water.

<u>Connecticut</u>: permits municipalities to exempt solar equipment from property taxes for 15 years after construction.

<u>Georgia</u>: solar equipment is exempt from sales tax and from property tax.

<u>Hawaii</u>: allows a property tax exemption and a credit of 10 percent of a solar system's cost against personal income tax.

<u>Idaho</u>: permits individual taxpayers an income tax deduction of 40 percent of the cost of new or retrofit systems in the first year, then 20 percent for the three following years, up to $5,000 per year.

<u>Kansas</u>: allows a 25 percent income tax credit up to $1,000 for residences and $3,000 for commercial buildings.

<u>Maryland</u>: grants city and county governments the power to allow credit against property taxes.

<u>New York</u>: exempts solar heating equipment from property tax assessments.

<u>Vermont</u>: permits towns to offer property tax exemption.

While the conversion to solar heating in an existing house (retrofitting) may be economically marginal, there are certain tax advantages to including solar heating in new construction. If the cost of the solar installation is covered by the mortgage, then the monthly interest and principal payment on this portion of the loan can be considered to replace the usual utility bill for oil, gas, and/or electricity. The interest payment is tax deductible, and the principal represents a capital investment rather than an operating cost. It is as if you were buying your own little utility company.

There are perhaps factors other than economic that might be worthy of condideration. A solar heating system makes one a bit more independent; the sun is perhaps more predictable than those who decide upon oil embargos or wars. There is something very basic about returning to the sun for its direct energy. You know that you are not contributing to the degradation of the environment and you are not tacitly approving the plundering of vast areas of land by strip mining, the polluting of the coastal areas and fishing beds by oil spills, or the potential problems of nuclear wastes. Even now there are a few idealists who are ready and willing to shake the fossil fuel habit; others will wait until the dollar sign beckons, and that may be sooner than you think.